JOURNAL OF THE INSTITUTION OF CIVIL ENGINEERS.

No. 5. 1935–36.
MARCH 1936.

ORDINARY MEETING.

11 February, 1936.

Mr. JOHN DUNCAN WATSON, President, in the Chair.

The PRESIDENT said that, out of respect for the memory of their beloved King George, the Ordinary Meetings had been suspended until that evening. Before the ordinary business was resumed he proposed to submit for their approval Addresses to His Majesty King Edward VIII and to Her Majesty Queen Mary. He would endeavour to express how deeply mourned was the death of a Sovereign who was more loved by his subjects than were any of his predecessors. King George was so essentially English in all his ways; his love for the Christian home, for the sea, the countryside and the theatre, as well as his interest in sport of all kinds, engendered sympathy with all classes of his subjects. A former Minister of the Crown, who was in close touch with King George for many years, once said to a friend of the President that the dominating characteristics of the King were his simplicity, his straightforwardness, and his intense devotion to duty, all of which were essential qualities in building up and strengthening the close bond between the Crown and the people; those qualities were exhibited at a time when such bonds were vanishing in nearly every country in Europe. The nation had lost a King who had done more for his people than words could express. They could not show their affection for his memory better than by unfailing loyalty to his son, who, like his beloved father, placed service before self.

The PRESIDENT then read the following two Addresses :—

"To His Most Gracious Majesty King Edward VIII.

"May it please Your Majesty—

"We, the President, Council, and Members of all grades of The Institution of Civil Engineers in meeting assembled, beg

leave most respectfully to offer to Your Majesty an expression of our profound grief in the great loss suffered by Your Majesty, Her Majesty Queen Mary, and the other members of the Royal Family by the death of King George V, our beloved Sovereign and Patron.

"King George will ever be remembered as the Monarch who won the love of his subjects by upholding their highest ideals and by his unsparing devotion in the service of the Empire.

"In submitting our dutiful and heartfelt sympathy, we desire also to assure Your Majesty of our loyalty and devotion, and we pray that God will grant Your Majesty good health and a long and peaceful reign over a happy and contented people."

"To Her Majesty Queen Mary.

"May it please Your Majesty—

"We, the President, Council, and Members of all grades of The Institution of Civil Engineers in meeting assembled, beg leave most respectfully to express our heartfelt sympathy in the bereavement sustained by Your Majesty and the other members of the Royal House by the death of our beloved Sovereign and illustrious Patron.

"In participating in the general grief, we mourn in His late Majesty one whose interest in The Institution of Civil Engineers was evinced when he was graciously pleased to honour The Institution by becoming an Honorary Member in 1893, and subsequently granting his patronage during his reign.

"We are conscious of Your Majesty's gracious influence in the achievements associated with King George's reign which secured for him the love and devotion of his people, and we pray that God will grant you courage and fortitude in Your Majesty's bereavement."

The Addresses were assented to in silence.

The Council reported that they had recently transferred to the class of

Members.

Harold Cholmley Mansfield Austen, C.B.E.
John Leslie Beckett.
John Durham Bird.
Oscar Borer, B.E. (*New Zealand*).
Cecil Brian Hugh Colquhoun, B.Sc. (Eng.) (*Lond.*).
William Harold Arthur Court.
Cecil John Dekema, B.Sc. (*S. Africa*).
James Elliott, B.A., B.A.I. (*Dubl.*).
Joseph Arthur Ellis.
Kenneth John Hier Evans, B.Sc. (Eng.) (*Lond.*).
Frank Fairchild Fergusson.
Robert Edward Snow Fisher, M.C.
Percy William Fryer.
Alfred John Gould, M.Sc. (*Lond.*), Ph.D. (*Cantab.*).
Charles Greenwood.
Wilfred Eric Randall Gurney.
Henry Lewis Guy.
William Paul Haldane, B.Sc. (*Glas.*).
Roy Hesseltine Hammett.
Isaac Harpur.
Percy Charles Greenwood Hausser, B.Sc. (Eng.) (*Lond.*).
Bernard Arthur Ernest Hiley.
Henry Hills, M.B.E.
Michael Anthony Hogan, D.Sc. (Eng.) (*Lond.*), Ph.D. (*National*).
Felix John Hookham, B.Sc. (*Manchester*).
Walter John Houghton.
Benjamin Williams Huntsman, B.Sc. (Eng.) (*Lond.*).
John Jagger, B.Sc. (*Leeds*).
Robert Trafford James.
George Jerram.
Arthur Stewart Johnston, M.C.
John Sinclair Kennedy, M.C., M.A., B.Sc. (*Glas.*).
Frederick August Klouman.
Rupert Grenville Knight, M.C., M.C.E. (*Melb.*).
Alexander Paterson Laing, B.Sc. (*Edin.*).
Eric Carl Lightbody, M.C.
Edward Alexander Logan, M.Sc. (*Durham*).
Charles John McKenzie, C.B.E.
Walter Patrick Fairrie McLaren, B.Sc. (*Cape Town*).
Harold Stanley Matthews.
Narayan Vinayak Modak, B.E. (*Bombay*).
Professor Kenneth Neville Moss, O.B.E., M.Sc. (*Birmingham*).
Reginald William Mountain, B.Sc. (Eng.) (*Lond.*).
Erach Ardeshir Nadirshah, B.Sc. (*Edin.*), B.A., B.E. (*Bombay*).
Arthur Holden Naylor, M.Sc. (*Birmingham*), B.Sc. (Eng.) (*Lond.*).
Arthur Charles Pallot, M.B.E., B.Sc. (Eng.) (*Lond.*).
Norman Augustus Victor Piercy, D.Sc. (Eng.) (*Lond.*).
John Kyle Prendergast, M.E. (*National*).
William Hilary Prendergast, B.E. (*National*).
Crosland Smith Richards, B.A. (*Cantab.*).
Allan Nelson McInnes Robertson, B.A., B.E. (*Royal*).
George MacLeod Ross, M.C., M.Eng. (*Liverpool*).
George William Scriven.
Cornelius John Scudamore.
Ernest Shaw, M.C., M.Sc.Tech. (*Manchester*).
John Grice Statter.
Charles Bruce Townend, B.Sc. (Eng.) (*Lond.*).
Henry Charles Watts, M.B.E., D.Sc. (*Bristol*).
Alexander Webster.

And had admitted as

Students.

George Russell Aldersley.
Iain Mackintosh Bain, B.Sc. (*Edin.*).
Michael Laurence Wolfe Barry, B.A. (*Cantab.*).

Michael Vivian Duncan Braine.
Charles Wilfred Brown.
William Henry Newlin Calver.
Ian Gordon Croxford.
Boris Cymbal.
Edmond Albert Dasnieres.
Gwilym Daniel James Davies.
George William Dowling.
Frederick Charles Egerton.
James Nicholson Garden.
Arthur Greenwood.
Bert Grimshaw.
John Roy Hammond, B.Sc. (Eng.) (*Lond.*).
Charles Frank Hewson.
Rowland Gordon Hocking.
Bruce Lancelot Fortescue Hubbard, B.Sc. (Eng.) (*Lond.*).
Peter Foster Johnson.
James McFarlane Kesson, B.Sc. (*Glas.*).
Kenneth Lanham.
Douglas Leatherland.
Derick Raymond Linfield.
Angus Sim MacKay, B.Sc. (*Aberdeen*).
Ronald William Alexander MacKichan.
Robert Brownlee Masterton, B.Sc. (*Edin.*).
Gordon Robert Mitchell.
Carl Ernest Mumme.
Eric Billingham Nash, B.Sc. (*Birmingham*).
Cecil Richard Newton-King, B.E. (*New Zealand*).
Francis Victor Osborne.
John Stuart Parson.
Thomas Michael Partridge.
James Whitelaw Pool.
Herbert Wilkinson Rhodes.
Roy Carr Thomas Richardson.
Dennis Frederick Rolt, B.Sc. (Eng.) (*Lond.*).
John Balfour Ross, B.Sc. (*Edin.*).
Russell Challen Saunders.
Charles Anthony Serpell, B. Eng. (*Sheffield*).
John Speight.
Frederick Burnett Tatton.
Harry Charles Taylor.
Paul Taylor.
Eric Turner.
Douglas Walpole.
Neville Craven Whitaker.
Edgar Burke Wilson, B.Sc. (*Belfast*).

The Scrutineers reported that the following had been duly elected as

Members.

Herbert Kenneth de Kretser.
Percy Harry Illingworth Humphreys, O.B.E.

Associate Members.

Alexis Banister, B.Sc. (Eng.) (*Lond.*) (Stud. Inst. C.E.).
Frank Seymour Ashwell Bather (Stud. Inst. C.E.).
George Ronald Baxter (Stud. Inst. C.E.).
Raymond Arthur Lewis Beeney, B.Sc. (Eng.) (*Lond.*) (Stud. Inst. C.E.).
Richard Thornton Betts, B.Sc. (Eng.) (*Lond.*).
Maurice Francis Brick, M.A., B.A.I. (*Dubl.*) (Stud. Inst. C.E.).
Thomas Patrick Browne, B.Sc. (Eng.) (*Lond.*) (Stud. Inst. C.E.).
James Alexander Chew (Stud. Inst. C.E.).
Kyrle Alan Clark, B.A. (*Oxon.*) (Stud. Inst. C.E.).
John Reginald Concher.
Alan Fullforth Dobson, M.A. (*Cantab.*) (Stud. Inst. C.E.).
John Howard Fennell.
Harold Gayton (Stud. Inst. C.E.).
James Halliday, B.Sc. (*Edin.*) (Stud. Inst. C.E.).
Kenneth Millington Harper, B.Sc. (Eng.) (*Lond.*).
Archibald Roy Hector (Stud. Inst. C.E.).

Geoffrey Holden (Stud. Inst. C.E.).
Egbert James Neville Holder (Stud. Inst. C.E.).
Roy Vivian Hughes (Stud. Inst. C.E.).
Frank Storer Jackson, B.A. (*Cantab.*) (Stud. Inst. C.E.).
Arthur Frederick Kelley, B.Sc. (*Durham*) (Stud. Inst. C.E.).
Leonard Nevill King, B.Sc. (Eng.) (*Lond.*).
William Herbert King, B.Sc. (*Durham*) (Stud. Inst. C.E.).
Geoffrey McLeod, B.Sc. (*Manchester*) (Stud. Inst. C.E.).
Basil Norman Maggs, B.Sc. (Eng.) (*Lond.*) (Stud. Inst. C.E.).
Charles Crommelin Marshall, B.Sc. (Eng.) (*Lond.*) (Stud. Inst. C.E.).
John Bernard Blount Newton, B.Sc. (Eng.) (*Lond.*) (Stud. Inst. C.E.).
John Frederick Mayo Perrott.
William Phillips, M.Eng. (*Sheffield*) (Stud. Inst. C.E.).
Leslie Samuel Podmore (Stud. Inst. C.E.).
William Brown Ramsay (Stud. Inst. C.E.).
David Moncur Kennedy Reid (Stud. Inst. C.E.).
John Stanley Rosbotham (Stud. Inst. C.E.).
John Walker Scott (Stud. Inst. C.E.).
Walter Henry Scott (Stud. Inst. C.E.).
Ralph Annand Simpson, B.Sc., B.E. (*New Zealand*).
Harold John Smith.
Richard Waddell, B.Sc. (*Edin.*) (Stud. Inst. C.E.).
Coulton Walker-Smith, M.A. (*Cantab.*).
Robert White, B.Sc. (*Glas.*) (Stud. Inst. C.E.).

Associate.

Vernon Harbord.

The following Paper was submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Author.

Paper No. 5047.

"The River Foyle Crossing (Londonderry Waterworks)."

By Walter Criswell, O.B.E., M. Inst. C.E.

TABLE OF CONTENTS.

Introduction.

The City of Londonderry lies in the valley of the river Foyle, 4½ miles above the point at which the river enters the Lough. The inhabitants to-day number nearly 50,000, of which the majority live on the north-west bank of the river, near the service reservoirs supplying them with water. This area is closely surrounded on three sides by the Irish Free State, with the river Foyle forming the fourth side, and its only connection with the remainder of Northern Ireland is a double-decked steel bridge for both road and rail transport.

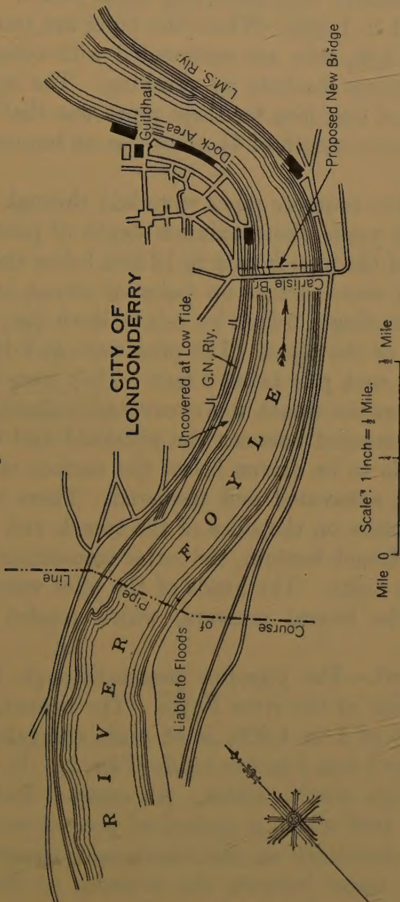
During early investigations into possible sources of water-supply, catchment-areas in Co. Donegal to the north and west were examined, but in view of recent political developments, it is perhaps fortunate that the source finally chosen was to the south-east, in Northern Ireland. It was recognised at the time that the tidal river Foyle would form a serious obstacle to bringing in a supply from this direction, but after a general consideration of the problem it was decided to proceed with the scheme, and the Act authorising the Banagher Water Scheme as a whole was authorised by the British Parliament in the year 1918.

This Scheme included a 500-million-gallon impounding-reservoir (recently completed under the direction of the Author) in the Sperrin mountains, a pressure-filter installation to deal with 3 million gallons per day, with provision for extension to 3½ millions, and a pipe-line 20·6 miles in length between the impounding-reservoir and the existing service-reservoirs on the north-west bank of the river (*Fig. 1*).

The Pipe-Line.

The construction of the conduit was begun in 1927 and was completed in 1930. The pipe-line was laid up to the margin of the river Foyle on both sides, details of the river-crossing itself being left for future consideration.

Fig. 1.



Site of Crossing.

The Siphons.—The eight siphons on the line are constructed of steel and cast iron, steel pipes ⅜ inch thick, lined internally with ¼-inch bitumen and coated externally with a double wrapping of hessian soaked in bitumen, being used where the static head exceeds 400 feet. The internal diameter of all siphons, other than the Foyle siphon, is 20 inches, with an hydraulic gradient of 1 in 333; the

estimated capacity is from $3\frac{1}{2}$ to 4 million gallons per day, according to the condition of the pipes. The Foyle siphon is 18 inches in diameter on either side of the actual river-crossing, with an hydraulic gradient of 1 in 200.

Concrete Pipes.—The non-pressure lengths between the outlet and inlet wells of the siphons are reinforced spun-concrete pipes 24 inches in diameter, with cemented collar-joints. They are laid to a gradient of 1 in 1,000. Where the pipes are buried to a depth of more than 12 feet, they are surrounded with cement-concrete to protect them against fracture by crushing. The reason for using concrete instead of cast iron for these pipes was that of economy in first cost, which on a length of $4\frac{1}{2}$ miles was an important consideration.

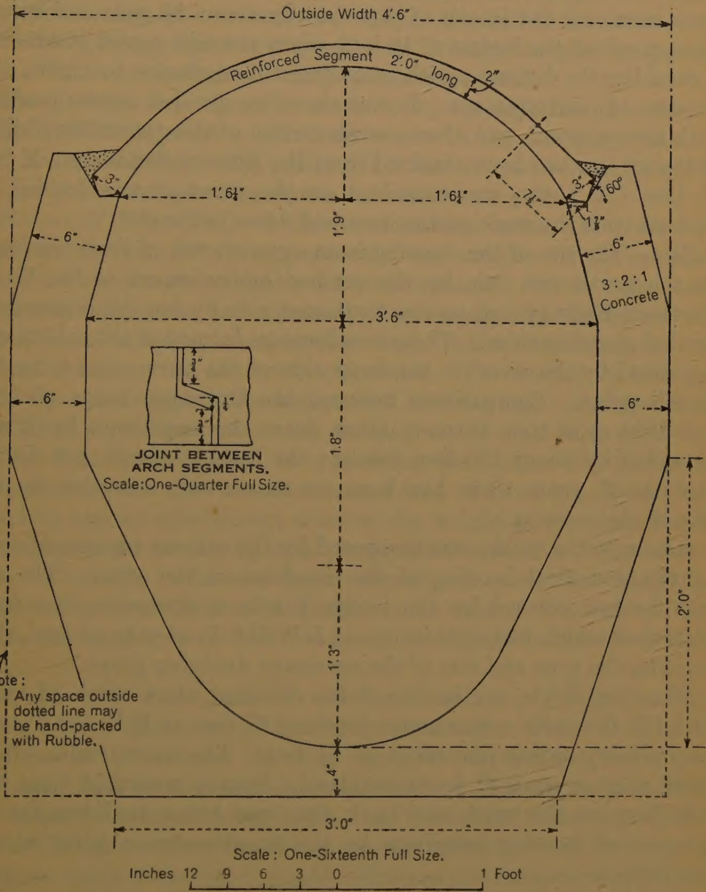
At one point the concrete pipes were laid through a peat bog for a distance of 426 yards, the maximum depth of peat being 28 feet, with the invert of the pipe from 4 to 12 feet below the surface of the bog. The pipes were carried on pairs of round larch piles with 6-inch tips, supporting a 6-inch by 8-inch larch cap, which was cut to fit the radius of the pipes. The piles were at 2-foot centres, the interval between each pair being 6 feet. They were driven down to solid ground before the trench was excavated, a short length of round timber being interposed between the pile-head and the "monkey" to enable the pile to be driven below the surface of the bog. The trench was then excavated and timbered. There was a considerable inward pressure on the sides of the trench and a large upward pressure on the trench-bottom, the latter sometimes rising a foot or more during the night. The heads of the piles were strutted apart to counteract the lateral pressure, which tended to force them together.

Corrody Tunnel.—The pipe-line passes through Corrody hill on the south-east side of the river Foyle. The tunnel, 471 yards long with a gradient of 1 in 1,000, is of mass concrete, and measures 3 feet 6 inches by 4 feet 8 inches inside (*Figs. 2*). It was driven from both ends through granite schist. An unusual feature is the construction of the roof, which is formed of precast reinforced-concrete arch-slabs 2 inches thick at the crown and 3 inches thick at the haunches. The space between the extrados of the arch and the rock cutting is drained towards the lower end of the tunnel to prevent external water-pressure. The tunnel was constructed by contract at a cost of £5,727, or £12 3*s*. per yard run, the contractors being Messrs. R. Colhoun, Ltd.

From Corrody tunnel the pipe-line drops down towards the river Foyle to the site of the crossing. On the opposite bank it crosses under the main line of the Great Northern Railway, passes over

the crest of the adjoining range of hills, and finally discharges into the Creggan Middle reservoir, the principal service-reservoir for the north-western area of the city.

Figs. 2.



SECTION THROUGH CORRODY TUNNEL.

RIVER FOYLE CROSSING.

The original scheme for crossing the Foyle comprised a reinforced-concrete trestle-bridge carrying a steel pipe-line. This proposal met with strong local opposition, principally on account of its alleged interference with navigation rights, and the Act, as finally passed, provided for a pipe " laid on or under the bed of the river."

The Author, however, on appointment in 1929 as chief engineer of the works, investigated the possibility of carrying the pipe-line along the lower deck of a steel bridge over the Foyle, $\frac{3}{4}$ mile below the proposed site of the crossing; this bridge was then about to be erected to replace an existing structure. This arrangement would have increased the length of pipe-line by about $1\frac{1}{2}$ mile and would have involved the laying of 18-inch pipes through paved streets for a considerable distance, with consequent disturbance to traffic and expense of reinstatement. It was therefore decided not to proceed with this proposal, and after a confirmation of the general feasibility of the scheme had been obtained from Mr. Edward Sandeman, M.Sc., M. Inst. C.E., who was consulted on the point, it was decided to proceed with the work on the lines laid down in the Act.

Site.—The site of the crossing is an open stretch of river bordered on the north-west side by the pitched embankment of the Great Northern Railway and on the south-east side by low-lying meadows flooded at spring tides. These meadows are formed of silt, which was deposited by the river on the inner side of the curve that it makes at this point. Comparisons between the Ordnance maps of 1832 and 1907 show that between these dates the south-east bank was extended by about 150 feet towards the opposite bank, but during the last 25 years there has been no measurable accretion on the line of the crossing.

Access to the works was hampered by the railway on one side and by the periodical flooding of the meadows on the other. The site was further isolated by the bridge $\frac{3}{4}$ mile downstream, the main girders of which had a clearance at L.W.O.S.T. of only 14 feet, thus limiting the type and size of the necessary dredging plant.

The river Foyle, on the line of the crossing, has a width of water of 1,125 feet with a maximum depth of 37 feet at H.W.O.S.T., and an ordinary spring-tide range of $7\frac{1}{2}$ feet. The exact width of the river was ascertained by triangulation from a measured base, 350 feet long, on the south-east bank, this base being used also for the purpose of locating soundings by the simultaneous reading of two theodolites.

Although the laying of the pipe-line on the surface of the river-bed was permitted by the Act, and would have resulted in a saving in immediate expenditure, the proposal was rejected for the following reasons:

1. The river being navigable for barges and small steamers, damage from anchors might be anticipated, and the covering of the pipes with a protective layer of the necessary thickness would be objected to by the various persons concerned.

2. The bed was not stable, sections taken at intervals showing a

lowering after heavy floods. The extra scour due to the presence of an exposed pipe would tend to erode the bed on the downstream side, with resultant deformation and possible fracture of the pipe-line.

3. Divers reported a noticeable to-and-fro movement of sand-particles during the ebb and flow of the tide, and it was considered that this moving sand would quickly cut through the pipe-wrappings and eventually through the metal of the pipe itself.

The decision was therefore made to lay the pipe-line in a trench (Fig. 3, Plate 1), with a minimum cover, in the navigable part of the river, of 3 feet. An additional 2 feet of cover was provided by the stone-and-gravel mattress referred to on p. 201.

Nature of River Bed.—A line of boreholes across the river had been driven some 13 years previously, and samples of the material from the bores were available for examination. On the south-east or meadow side, the bed consisted of extremely fine silt which was capable of carrying considerable loads when undisturbed, but formed a slurry when saturated with water. To ascertain its bearing-capacity a testing-platform was erected between high- and low-water marks, at a point where a man walking would sink halfway to the knee. Test loads applied to a circular steel plate $13\frac{1}{2}$ inches in diameter showed that at 4 feet deep a load of 1 ton per square foot could be carried indefinitely, whereas the weight of the pipes full of water amounted to only $1\frac{1}{4}$ cwts. per square foot of area at the centre-line. From the south-east bank towards the north-west bank the particles increased in size, becoming coarse sand in the centre of the river, and hard gravel, with occasional boulders, on the north-west side.

Rough tests were made to ascertain whether a dredged trench would remain open long enough to lay pipes in it. Holes were made by divers in the centre of the river (sand bottom) and near the south-east bank (silt bottom), and it was observed that these holes filled up within 24 hours of being made. As a result of these tests it was realized that, to allow for silting up, the trench would have to be dredged much wider than would otherwise be necessary, and that the correct initial depth of the dredged trench would have to be ascertained by experience as the work proceeded. In addition, it was obvious that the laying of the pipes must follow immediately after the dredging and that both dredging and pipe-laying must proceed continuously, as otherwise, having regard to the method proposed to be used, the work could not be carried out successfully.

Sections of the river were taken from a rowing-boat, manned by a boatman, an observer to manœuvre the boat on to the section-lines and to signal to the theodolite-observers on the shore, and a leadsman

to take the soundings. Up to a depth of 15 feet a dip-rod was used, and above this depth a weighted steel wire with brass tabs at each foot and smaller tabs at each 3 inches. The distances from the zero point on the shore were obtained by calculation from the readings of two theodolites on the measured base-line on the south-east bank, sights being taken at the moment of sounding on to a white-painted ball-topped rod which was fixed in the bows of the boat.

The velocity of the current at different points across the river was ascertained by a Watts current-meter, which comprised a revolution-counter actuated by a propeller, fitted with a vane to keep the propeller facing the current. The apparatus was attached to a short steel rod weighted at the bottom with a 21-pound lead weight to keep the rod vertical and was lowered from an anchored boat to the required depth. The maximum velocity ascertained by this means was 215 feet per minute (2·44 miles per hour) at 1 foot below the surface and 205 feet per minute (2·33 miles per hour) at 1 foot above the bottom on the ebb of a spring tide, and slightly less velocities on the flowing tide, but higher velocities than these occur occasionally.

Capacity of Pipes.—The difference between the invert-level of Corrody tunnel, which passes through the ridge on the south-east side of the river, and that of the pipe-line crossing the ridge on the north-west side allowed a steeper hydraulic gradient to be used on the Foyle siphon than that on the other seven siphons. For convenience of laying, and to provide an alternative supply in case of mishap, the conduit under the river was divided into two lines, and it was calculated that, in combination with an 18-inch siphon, two lines of 12-inch pipes for the river-section would carry about 4 million gallons of water per day according to their condition and that, in the event of a breakdown of one of the lines, the other, used by itself, would carry 3 million gallons, or three-quarters of the full supply.

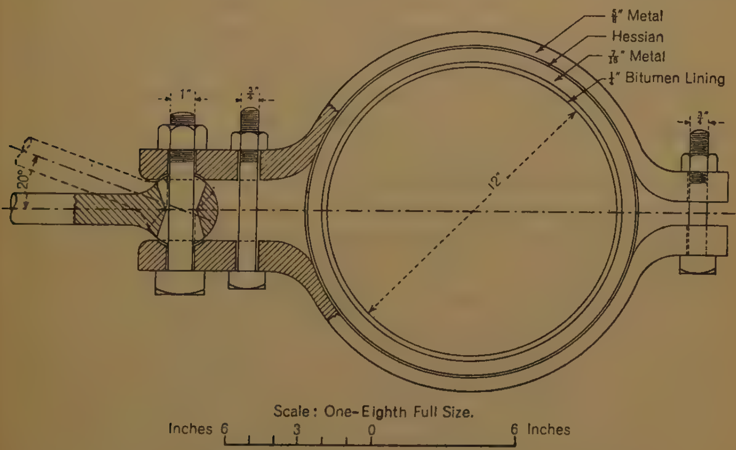
Flexible Joints.—Fourteen ball-and-socket joints (Figs. 4, Plate 1) were introduced at intervals into each of the two pipe-lines to enable them to follow the general contour of the river-bed. These ball-and-socket joints weighed 8½ cwts. each and were of cast steel, heavily galvanized to the standard Admiralty specification. They were designed for a maximum angular movement from the centre-line of 30 degrees in any direction (the maximum practicable, for manufacturing reasons), and were fitted with an annular stop operating when this 30-degree limit was reached. The joints were tested at the makers' works to a hydraulic pressure of 400 pounds per square inch and to various lesser pressures, the tests being made while the joints were in three different angular positions.

The question of the stresses likely to be caused on the ball-and-

socket joints during various methods of pipe-laying was also examined. Considering a single line of pipes, the direct tensile or compressive stresses were found to be well within the capacity of the joints, but with a 100-foot pipe-section attached, high flexural stresses could be transmitted through the annular stop when the angular movement reached 30 degrees. The maximum permissible angular movement during the process of laying was therefore limited in the specification to about 25 degrees, and this angle was only exceeded on one occasion, as described on p. 201.

Longitudinal compressive stresses transmitted along the pipe-line during laying would tend to lift the previously-laid ball-and-socket joint where this was at an external angle, and concrete weighting-blocks laid by divers were provided to counteract these stresses.

Fig. 6.



HALF ELEVATION OF CROSS LINK.

Allowance was also made for the vertical component of the stress caused by the hydrostatic pressure of the water under working conditions; this amounted to a maximum of 0·8 ton for any joint.

Considering the two lines of pipes, if these were laid in one operation and braced together to form a horizontal girder measuring 4 feet between the centres of the flanges (Figs. 5, Plate 1), the total longitudinal tension on the joint A, with a current-velocity of 4 feet per second, would amount to 28½ tons, a load for which the joint was not adapted and which might be appreciably increased during the operations of pipe-laying.

The two pipe-lines were therefore connected together with steel cross links fitted with small ball-and-socket joints to allow free movement in pre-arranged directions (*Fig. 6*).

Steel Pipes.—The steel pipes were of $\frac{7}{16}$-inch metal, double flanged, and of 12 inches diameter measured inside the $\frac{1}{4}$-inch centrifugally-applied bitumen lining. They were wrapped externally, to the base of the flanges, with three layers of hessian soaked in hot bitumen. The length of each individual pipe was fixed at 20 feet, both as a suitable proportion of the length of a pipe-section and also to avoid the distortion which takes place in longer pipes when over-hanging the end of a lorry.

Pipe-Flanges and Bolts.—The flanges were of wrought steel, welded on, having a thickness of $1\frac{1}{2}$ inch with 1-inch bolts for the 80-foot pipe-sections, and $1\frac{3}{4}$-inch with $1\frac{1}{8}$-inch bolts for the 100-foot pipe-sections. Bolts were of mild steel to B.S. specification, sixteen to each flange, galvanized after threading.

Joints for Flanges.—The joint-rings were of "Dexine" $\frac{1}{8}$-inch thick, and, being used under ideal conditions (that is, in compression, in complete darkness and free from air influence), no doubt is felt as to their permanency. Experiments had been carried out earlier on 12-inch flanged pipes which were available, using soft sheet-lead rings extending over the full width of the flange; owing, however, to slight irregularities in the flanges, the joints were not watertight under the high test-pressures used. The pipe-flanges supplied under the contract were, however, of such accuracy that the soft lead rings would probably, in practice, have made a perfectly watertight joint.

The Pipe-Trench.—Above low-tide level on the north-west side, the trench, sited in gravel, was excavated by hand. The remainder was excavated by a grab-dredger. The principal difficulty, as anticipated, was the tendency of the dredged trench to silt up before the pipes could be laid, or, where the trench ran through gravel, by the tendency for the sides of the trench to collapse. After the pipes had been laid in such cases the bed of the trench was lowered to the correct level by a diver, who removed any hard material with a hand tool, and removed silt with a compressed-air jet. In one case where both pipe-lines near the south-east bank were laid on silt 2 feet too high, the outside edges of the pipes were marked with stakes and a trench was then dredged on each side, into which the diver moved the silt from under the pipes. Generally, where the excavation was in silt, the trench, after dredging, was a saucer-shaped depression, and the dredger was kept working until the last possible moment before laying the pipes.

After the pipes were laid, the trench was refilled with material similar to that excavated; where, however, the trench was in silt or sand, it refilled itself without assistance in the course of a few tides.

Pipe-Sections.—One of the principles laid down for the work was that every joint must be made above the surface of the water, the only work to be done by divers being the placing of concrete weight-blocks over external angles, and incidental work required in bedding the pipes. This enabled the resident engineer personally to see each joint made and wrapped with its protective covering. The general lines of the scheme for laying the pipes developed naturally after the establishment of this principle. Most of the joints were made in the pipe-yard on the river-bank before the sections were floated out, leaving only the joints between the pipe-sections to be made over the surface of the river.

The length of the pipe-sections was designed to allow the leading ends of the sections to project clear of the water at low tide when they were making a vertical angle with the previously-laid section of not more than 25 degrees. A standard length of 80 feet between the ball-and-socket joints was found adequate, except for three sections in the deepest part of the river, where lengths of 100 feet were used. In the latter case, however, the pipes had to be left submerged at high tide in order to keep the movement of the ball-and-socket joints within the permissible angle.

Steel blank flanges were retained in position on the leading ends of the pipe-sections until the next section was about to be attached, as the specification required the interior of the pipes to be kept free from water during laying ; this was because the extra weight of the water would have added seriously to the stresses on the pipes and flanges.

Method of Laying.

Pipe-laying commenced on the north-west or railway side of the river and, except for the 38-foot length on that side, which was laid in the dry by ordinary methods, the scheme of operations was as follows :

Pipes were assembled on the south-east bank and bolted together to form sections of the required length, each section having a ball-and-socket joint at one end. The pipe-flanges and the exterior surfaces of the ball-and-socket joints (other than the machined surface of the ball) were coated thickly with hot bitumen and wrapped with three layers of hessian soaked in bitumen. Blank flanges were bolted to the open ends and the pipe-sections were tested with an hydraulic pressure-pump.

At low tide two sections were rolled down inclined ways to a platform constructed below the high-water mark, and sufficient

barrels were distributed along the sections and attached with slip-knots to give the necessary floatation. As the tide rose the sections were floated off the platform and, after being cross-connected with the steel links, were towed across the river and bolted at low tide to the flanges of the landward pipes, the ball-and-socket joints acting as hinges between the new and landward sections.

These ball-and-socket joints allowed the leading ends of the newly-attached pipe-sections to rise with the tide, so that at high tide the twin sections would be lying in an inclined position and making a vertical angle of not more than 25 degrees with those already laid. A pontoon was securely anchored on either side and the leading ends of the inclined pipe-sections were suspended by chain-blocks from an overhead gantry carried by the pontoons (Figs. 7, Plate 1). As soon as the weight was transferred to the chain-blocks the floatation-barrels were removed.

The next pair of pipe-sections, with ball-and-socket joints attached, was then floated out and bolted on to the suspended ends of the inclined pipe-sections. After wrapping the flanges with hot bitumen and hessian, the barrels were removed or regrouped as required, and the pair of ball-and-socket joints, now an integral part of the pipe line, were lowered by the chain blocks into their final positions in the dredged trench. The pontoons were in turn moved forward to the leading ends of the newly attached sections, now lying in the inclined position with their forward ends supported by a batch of barrels. This process was repeated until the opposite bank was reached.

Considering any three continuous sections of the pipe line, the landward section of 80 feet or 100 feet would be in its final position in the dredged trench, which would be either rapidly silting up, or in process of being refilled by hand, according to the nature of the river-bed; the middle length would be lying in a vertically inclined position, while the third length would be floating horizontally on the surface of the water, ready for sinking, in its turn, into the inclined position (Figs. 7, Plate 1). The dredger in the meantime would be excavating an 80-foot or a 100-foot length immediately ahead and would continue dredging until the last available moment before the next pipe sections were floated out.

Great care was used in anchoring the pontoons and also the floating sections of pipes, both up and down stream, on account of the current. In the case of the 100-foot sections, temporary support in the centre was given during the process of laying to assist in taking the rather severe flexural stress caused by the current. During the progress of the work the pipes already laid were tested at intervals with low-pressure air.

Mattress over Pipe-Line.—Cross sections of the river, taken in

February, 1927, and in August, 1929, showed that a lowering of the bed by as much as 2 feet 3 inches in depth had occurred during the intervening period, the year 1928 being one of exceptional rainfall and unusually heavy floods. The area principally affected was about 50 yards in width, between the seventh and ninth ball-and-socket joints (counting from the left) (Fig. 3, Plate 1), where the river-bed was in coarse sand. To protect the pipe-line against future scour, a stone-and-gravel mattress about 30 feet wide and 2 feet thick was deposited over it. There being little or no scour near the south-east bank, coarse gravel, dredged cheaply further up the river, was used here, with quarried stones of an individual weight of from 20 to 30 pounds for the centre and towards the north-west side. An inspection of the mattress by divers 9 months later showed that it was acting as anticipated; the gravel and sand had not been disturbed, while the large stones on the outer side of the curve, although undisturbed, had been swept clean by the current.

General Remarks.

Pipe-laying was begun at the end of July, 1930, and the pipes were ready for connection to the existing pipes on the opposite bank 2 months later. Prolonged hydraulic tests to a head of 500 feet showed both pipe-lines to be "drop-tight," and water was passed through the conduit under working conditions on the 31st October, 1930. The maximum hydrostatic pressure is 426 feet.

The work of laying steadily proceeded according to plan, the only mishap of any consequence being the breaking loose of one twin 100-foot section when lying in the inclined position, due to the fouling of the anchorage by a dredger. The section rotated slowly with the current until the full 30 degrees movement of the ball-and-socket joint was reached. After securing and getting the section back into position, the previous section, with its ball-and-socket joints, was raised for examination; it was, however, found to be undamaged, and was immediately relaid.

Control-valves were provided on each pipe line on both sides of the river, those on the south-east bank being carried on a reinforced-concrete platform on piles; reinforced-concrete blocks around the valves transmitted the thrust to the platform, any longitudinal movement of which was prevented by a curtain-wall of old tram-rails driven into the silt. On the north-west side the two pipe-lines were anchored to the concrete blocks under the Great Northern Railway, the flanged pipes being sufficiently strong to take any tensile stresses occurring in them. On the south-east side a sliding-

collar joint was inserted in each line, but during the 10 days that the joints were kept under observation after completion of the pipe-laying, no "draw" was observed.

The greater part of the Banagher Water Scheme was constructed by direct labour, but, in the case of the river Foyle crossing, it was considered advisable, in view of the specialized plant required for only a short period, to employ a contractor having the necessary plant facilities. Enquiries were therefore made amongst numerous public-works contractors throughout the United Kingdom as to whether they would be prepared to submit a tender. Of the four tenders eventually received two contained conditions which rendered them inacceptable. The final ascertained cost of the river crossing, exclusive of the test-boreholes, railway-crossings, control-valves and other work on each side of the river, was £12,642 17*s*. 6*d*.

The plant used on the work included a Priestman grab-dredger, which was assisted for a time by a second grab-dredger, two pontoons with the necessary pipe-handling plant, a portable petrol-driven air-compressor and a diver's outfit.

The steel pipes were supplied by Messrs. Stewarts and Lloyds and the ball-and-socket joints by Messrs. Glenfield and Kennedy. The high quality of the material and the precision of manufacture in both cases are worthy of mention.

The contractor was Mr. James Green of Belfast and the resident engineer was Mr. W. G. Davis. The work was carried out to the designs of, and under the direction of, the Author.

The Paper is accompanied by six sheets of drawings, from which Plate 1 and the Figures in the text have been prepared.

Discussion.

The AUTHOR showed a number of lantern-slides in illustration of the Paper. The Author.

Mr. EDWARD SANDEMAN mentioned that he had had the advantage of watching the building of the Banagher dam, and had much pleasure in recording his appreciation of the ability and care displayed by the Author, who was the engineer also for the design and construction of that work. The dam was situated in the hilly country about 20 miles south-east of Londonderry, in a valley which was very difficult of access. Any engineer who saw the exposure of the rock would have been struck by the unusual shallowness of the trench and the massive jointless appearance of the granite schist which formed the bed of the valley. The site, however, had the drawback that the rock on the hillside sloped extremely steeply, and, although in places the rock was very good, in others it was poorer, and much care was necessary when digging the foundations. One big slide of rock occurred which fortunately did no harm, but he had always been very uneasy with regard to slips. The method adopted by the Author, namely, that of digging headings into the hillside one above the other, and filling them up as the work proceeded, was ingenious and had proved most effective. Mr. Sandeman.

The dam was curved, with two wings and with an overflow in the centre, and, as first designed, there were only two contraction-joints, one on each side of the overflow, which was 77 feet in width. After a time he came to the conclusion that more contraction-joints would be required, and two more were accordingly put in, in order to divide the wings. At a later stage the wings were again divided by contraction-joints, which commenced at a much higher level, so that eventually the contraction-joints were about 30 feet apart. The result had been very satisfactory, and there was very little sign of movement other than one or two hair-cracks, and they only occurred where the contraction-joints were situated; there was no crack at any other point. The use of displacers in the concrete might have helped in the bringing about of this result, although they were only used to the extent of about 18 per cent. That was a very small quantity, and the stones put in were not of large size. In building other masonry dams he had been able to put in as much as 33 per cent. when using granite and as much as 42 per cent. with gritstone, where the stones were naturally cubical in shape. There was much less tendency for cracking to occur where there was a large amount of stone in the concrete.

Mr. Sandeman. The cracking of concrete was sometimes due to the presence of too much water. In a Paper[1] describing thirteen dams built in Australia it was mentioned that five of them had cracked, and, when Mr. Sandeman wrote to the Author of that Paper about the matter, he mentioned in his reply that probably the amount of water used had a good deal to do with the cracking of the dams. On one occasion he had had two dams built at the same time and of the same section, both being about 1,100 feet in length. The foreman in charge of one was accustomed to the use of dry concrete, while in the other case the foreman was used to what might be termed "sloppy" concrete. The dam for which the drier concrete was used had no crack in it, but the dam made with the wetter concrete had a crack through the centre.

Mr. Davidson. Mr. J. R. Davidson remarked that the Author was to be congratulated on having presented to The Institution a clear and concise account of a work which, while of no great magnitude possessed several very interesting features. There were two minor points to which he would like to refer. In the section dealing with the pipe-line, the Author stated that the steel pipes were wrapped with hessian saturated with bitumen. He had found by experience that if the hessian were merely saturated with bitumen it did not provide a permanent protection to the outside of the pipes. For some reason the hessian seemed to possess the property of absorbing the bitumen, and after a few years it would be found that the bitumen had assumed a brown colour. It soon began to rot, leaving the pipes with very little protection. He thought that the explanation for the use of that form of protection was afforded by the Author's statement that the pipes were laid between 1927 and 1930 because it was only about that time that the improved form of protection began to be introduced. With the improved form the hessian or paper was merely used as a carrier, and was employed to wrap from $\frac{1}{4}$ to $\frac{3}{8}$-inch of bituminous mixture on to the outside of the pipe. The hessian then served a second useful purpose, in that it protected the bituminous composition during transport. Once the pipe was laid, however, the hessian was no longer of use, and it was immaterial if it disappeared, as the solid sheathing of bituminous compound was left intact. That sheathing ought to last indefinitely.

The Author referred to the bolting of the flanges with mild-steel bolts. He was of the opinion that, where there was sufficient section in the flanges, it was worth while using wrought-iron bolts, owing to their increased life as compared with steel bolts. In the present

[1] L. A. B. Wade, "Concrete and Masonry Dam-Construction in New South Wales," Minutes of Proceedings Inst. C.E., vol. clxxviii (1908–9, Part IV.), p.

Mr. Davidson.

case, however, the Author had pointed out that the bolts were heavily galvanized after threading.

The Paper showed very clearly that all the details in connection with the laying of the mains across the river Foyle had been carefully worked out, and in such an operation that was the only way in which success could be achieved. The chief difficulty experienced during the laying of the pipe appeared to have been that of keeping the dredged trench open long enough to lay the pipe at the proper depth. He thought it might be of interest to say something about a method of sinking a pipe-line across a river which was adopted some 45 years ago by the late Mr. G. F. Deacon, M. Inst. C.E., in connection with the Vyrnwy pipe-line bringing water from Vyrnwy to Liverpool.[1] That pipe-line, which was some 66 miles in length, crossed the river Mersey at Fiddler's Ferry, half-way between Runcorn and Warrington, where the river was tidal and was over 800 feet in width. Whilst it was true that at low spring tides it was possible to wade across the river in thigh-boots, at high tide there was a very considerable depth of water, and the stream flowed with a greater velocity than was found in the case of the river Foyle.

The Act which authorized the original scheme required that the pipes should be laid across the river Mersey at a depth which compelled the construction of a tunnel. That tunnel was, according to Mr. Deacon's account (which Mr. Davidson believed to be correct), the first tunnel ever constructed under a tidal or other river by means of a shield driven through entirely loose materials. The work was extremely difficult; the first firm of contractors had driven practically no heading at the end of 41 months, whilst the second firm of contractors spent another 21 months, and only a quarter of the length of the tunnel had then been completed. The work was then finished by direct labour, and it was completed in 4½ months. During the long period of construction, however, Liverpool was in dire need of water. The pipe-line had been completed throughout its entire length with the exception of the river-crossing, and, in order to provide an emergency supply, Mr. Deacon laid a temporary main in the bed of the river, coupled up on each side to the already-constructed main pipe-line. The temporary pipe which was laid was about 15 inches in diameter.

Mr. Deacon floated the pipe across the river as a whole, and sank it in the sand and silt of the river-bottom by means of hydraulic jets. Mr. Davidson thought that the report which Mr. Deacon made on that work was of interest. It was quite a brief document,

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[1] "The Vyrnwy Works for the Water-Supply of Liverpool," Minutes of Proceedings Inst. C.E., vol. cxxvi (1895–96, Part IV.), p. 24.

Mr. Davidson. but it showed the great attention that Mr. Deacon paid to matter of detail. The report was dated 2nd June, 1891, and was a follows :—

"I beg to report that the launching of the steel tubes, intended fo temporary use pending the completion of the Aqueduct Tunnel under th Mersey, was successfully performed on the evening of the 31st May ultimo

"The peculiarities which distinguish the case under consideration fron any others in which, so far as I know, water mains have been laid are a follows :—

"1. The working pressure in the Vyrnwy Main at this point is abou 140 lb. per sq. inch.

"2. The width of the river at the point of crossing is about 800 feet.

"3. The low-water channel of the river (generally about 250 feet i width) travels from side to side for nearly the whole 800 feet o width, and occasionally moves in a single tide from one side t the other.

"4. The bottom of this channel is from 5 to 10 feet below the bank intermediate between the two shores, and about 16 feet belov certain portions of the banks liable to be washed away near th shores.

"5. This channel is, moreover, 16 feet below the high water of Sprin tides.

"6. Except just during the turn of the tide the velocity of the current even under the most favourable conditions—that is to say durin neap tides—would be at least 3 to 4 ft. per second past the pipe during the process of launching, and before they were sun beneath the bed of the river.

"Under these circumstances, it will be well understood that extra ordinary precautions were necessary to ensure success; but these pre cautions having been taken, I have never doubted the success of th undertaking.

"The tubes with their flexible joints were put together zig-zag upo cradles resting on launching ways, laid at right angles to the river o Cuerdley Marsh, Lancashire."

Mr. Davidson thought that the idea of putting the tubes zig-za was to provide for the extra length when the pipes settled down int the curves of the river-bed, so as to avoid putting any tension on th pipes.

"The zig-zag form was maintained during the launching by means four steel wire ropes, the lower pair connecting all the cradles and the upp pair connecting horizontal booms of timber lashed to the tubes at ever joint. These booms were destined to maintain the zig-zag in a horizont position upon the water, and to prevent the tubes from overturning.

"Thirty feet higher up the river than the intended pipes there we moored fore and aft, with their sterns downstream, eight 23-ft. riv boats, and across the sterns of these boats was tightly stretched from sho to shore a 30-ton steel wire guide cable. A second 30-ton steel cable f hauling was passed across the river in the intended line of the pipes to powerful steam winch on the Cheshire shore; this cable was connect with the ends of the four wire ropes holding the tubes in position.

Mr. Davidson.

"A tail rope of steel was used to control the motion, and horses with double-purchase tackle were used to assist in starting, making up the total horse-power for hauling purposes to twenty-two.

"One of the chief precautions necessary was to counteract the great lateral pressure upon the tubes due to the velocity of the water past them during the process of launching and that of sinking. For this purpose the boom across every alternate joint was connected by a steel guy rope to a block, the sheave of which ran upon the 30-ton guide rope held by the sterns of the boats.

"It was decided that upon the whole the safest time for the launch to begin would be at high water of a neap tide. Several suitable tides occurred before and after the end of May, and that of the afternoon of Sunday, the 31st ultimo, being the first tide after the necessary preparations had been made was selected for the operation.

"A preliminary trial having shown that all was free, the launch was begun without difficulty on the turn of the tide at 6.35 p.m.

"Twenty-seven and a half minutes later the Cheshire end of the tubes had been brought to its intended position. In about fifteen minutes more, a temporary connection having been made on the Cheshire side, the water was turned on and the tubes sank into their required positions. In less than an hour from the commencement of the launch, Lake Vyrnwy water was being discharged on the Lancashire shore.

"On the following morning the pipes were found to be below the bottom of the channel, and so flexible are the joints that the wash of the current is quite sufficient to keep them below, whatever may be the course taken by the channel.

"The hydraulic jets have been brought into play where the banks are dry at low water, and have completely buried the pipes.

"I apprehend no danger whatever to navigation. No traffic was stopped by the operation."

The sentence about the hydraulic jets required explanation. In the bottom of the pipe, at intervals of about 2 feet 6 inches, there were orifices closed by loaded valves. To the top of each valve was attached a length of piano-wire which passed through a watertight gland in the top of the pipe, the wire thus passing across the vertical diameter of the pipes. Outside the pipe a float was attached to the end of the wire. The result was that when the wire was pulled a jet of water under a pressure of 120 pounds per square inch rushed out of the orifice and scoured a hole, and the succession of those holes joined up into a trench and the pipe went down. Unfortunately, it was found that particles of sand and small gravel got between the valves and their seatings, with the result that there was a very considerable leakage from the main during the whole of the time that it was in use. However, it served its purpose, and it continued to work until the tunnel was completed.

In 1921, Mr. Davidson was engaged on the plans for the crossing of the same place by the third and fourth pipe-lines, and, as the existing tunnel was full with only two mains, he proposed to lay the

Mr. Davidson. new pipes in the bed of the river, and to sink them by means c hydraulic jets. Instead of using the main pipe itself for the suppl of water to the jets, he proposed to attach on each side of it a 6-inc pipe which would be fastened below the horizontal diameter by clip From those supply-pipes connections were to have been taken t nozzles attached to the bottom of the main pipe. Each connectio between the supply-pipes and the nozzles was to have been controlle by a cock with a rigid spindle carried up above the water-level. H had had a model made of this, and he believed that some of th members present that evening had actually seen that model at worl It was made on a practical scale, and was at first so arranged that th jets discharged in both directions; as might be expected, howeve he discovered that that method would not work, because tw opposing jets counteracted each other, and the result was a series c holes near the jets, with heaps of sand in between. As soon, howeve as the jets were all made to discharge in the same direction, namel along the line of the pipe, there was no trouble in scouring a trencl and it was possible to put a pipe down so quickly that it could b seen gradually sinking into the sand. There was no reason to believ that it could not have been sunk to any depth required in tha material, up to about 10 feet of cover. The river authorities di not agree to the proposal to lay the pipes in the bed of the rive however, and they compelled the construction of a second tunne That work had just been started by Mr. Frank Hibbert, M.C M. Inst. C.E., with Dr. W. L. Lowe-Brown, M. Inst. C.E., as con sultant.

Mr. Hill. Mr. H. P. Hill said that the absence of any mishap during th work described was notable, and showed the foresight and care tha had been exercised in the preliminary stages and during the con struction. The work carried out was somewhat unusual, and wa in a tideway where various contingencies could not always b anticipated. He thought that the Author exhibited a great deal c courage in choosing the method adopted for crossing the river i preference to utilizing the bridge, and he congratulated him on th excellence of the work in getting the main "drop-tight." It wa often necessary to carry pipes, either for drainage or water-suppl across navigable waterways. He had come across one case, on th river Nile at Mansura, where the pipe was taken across the river t supply water to the other side; no one had had the courage to pu the pipe under the bed of the river, and it was carried on the rai way bridge. The bridge had to be moved every time a boat passe and the result was that the pipe had to be severed each time— somewhat lengthy proceeding. A longitudinal section of the typ of joint used at Londonderry would be of interest. There we

many different commercial designs of ball-and-socket joint; he wondered whether the Author had adopted the "Carlton" joint. Mr. Hill.

Mr. Davidson had described the adventures of Mr. G. F. Deacon in laying a pipe across the river Mersey in 1891; the Paper showed the advance which had been made in the technique of such work since that date. The methods adopted by the Author had proved so satisfactory that they did not call for any criticism.

Mr. G. M. C. TAYLOR remarked that he would like a little more information on one or two points, especially with regard to the laying of the pipe-line across the river, as he anticipated that he might have to deal with a very similar problem. Mr. Taylor.

The Author mentioned that reinforced spun-concrete pipes were used for a non-pressure length of pipe-line. He had recently carried out some drainage work in Northern Ireland, and had found that he was able to get concrete pipes of excellent quality, both circular and egg-shaped. Where there was no internal pressure he would prefer the pipes to be without reinforcement. He noted that each section of the pipe-line was floated out on barrels, and he assumed that the barrels were necessary in order to get the joint entirely above water-level, so that it could be made in the dry. He would like to ask whether the section itself would float without any barrels, or whether the joint at the end would be too heavy, as he imagined that a sealed 12-inch steel tube would float. The Author stated that in the case of the 100-foot sections temporary support in the centre was given during the process of laying. It would be interesting to know how that temporary support was given.

The only other comment which he desired to make was on the way in which the pipe was duplicated under the river. The object of duplication was to reduce the possibility of an accident from cutting off the complete supply. The chief dangers to be anticipated were from the anchor of a ship catching hold of the pipe-line and damaging it, and from a barge or ship sinking and lying on top of the pipe. It seemed to him that with the two pipes situated so close together, and cross-braced, the object aimed at would not be achieved, and that for true duplication it was necessary to have them very much farther apart. He thought that it would have been better either to have laid a single pipe or to have laid duplicate pipes so far apart that both were not likely to be damaged by dragging anchors or sunken ships.

Mr. H. W. S. HUSBANDS remarked that about 32 years ago, he had been connected with the sinking of an 18-inch steel pipe across the river Avon at Bath. The river at that point was only about 100 feet in width, and the interesting point about the work was that it was proposed at first to employ divers either to get the pipe Mr. Husbands.

Mr. Husbands. down or to join the sections under water. The contractor's engineer suggested another method, however, which was accepted, although some people had such doubts as to whether it would be successful that a wager was laid on the result. The engineer won the wager. He believed that the tide went up as far as Bath, but the river was not navigable to any extent at that point. The method adopted was to put a gantry across the river, and to grab out a trench, the whole length of pipe being lowered together by screw-jacks. He could not remember whether the bends were attached beforehand or whether a cofferdam was afterwards laid around each end of the pipe to finish off the work. The difficulty which was expected was that the pipe would be strained by the jacks not working evenly, but by means of signals it was found possible to keep the jacks turning equally, and no difficulty occurred.

The Author referred to the calculations adopted for the purpose of seeing that the pipes were not over-stressed, and on p. 197 of the Paper he said, "Allowance was also made for the vertical component of the stress caused by the hydrostatic pressure of the water under working conditions; this amounted to a maximum of 0·8 ton for any joint." He would like to ask what the Author meant by that statement, as it was not very clear to him. It seemed to him that in the case of a pipe of the type used the only external water-effect which would be obtained on the pipe would arise from the buoyancy of the river itself. If the Author was referring to what was generally known as the "uplift," it was true that it had been stated that with a pressure-pipe there would be some uplift from it, and that consequently if it were put under the ground it would have to be taken to a certain depth to avoid the effects of uplift. A Paper[1] had been read before The Institution in which a similar calculation had been made, and he had pointed out on that occasion that in the case of a tube the hydraulic head resolved itself into either pressure or velocity, and there was no external effect since the pressure was acting entirely within the tube. If that was not what the Author had in mind, he would ask him to explain what he meant.

He did not know whether or not ball-and-socket joints were so finely machined nowadays that they worked without any packing, and perhaps the Author would inform him as to whether any packing was used. The Author stated that packing was used in the case of the ordinary joints, but had given no corresponding information with regard to the ball-and-socket joints. It would also be interesting to know whether the Author had considered using some such

[1] G. Haskins, "The Construction, Testing, and Strengthening of a Pressure Tunnel for the Water-Supply of Sydney, N.S.W.," Minutes of Proceedings Inst. C.E., vol. 234 (1931–32), p. 25.

joint as the "Victaulic." That joint allowed a certain degree of flexibility, but perhaps not sufficient for work of the kind in question. Mr. Husbands.

Mr. Taylor had asked whether the pipes would not have floated without the aid of barrels had they been full of air and with their ends sealed. Had they been able to do so, however, it would appear that they would not have sunk when necessary, and weights would therefore have been required to sink them.

In conclusion, he would like to congratulate the Author on the conciseness of his Paper, on the very interesting nature of the work described, and on its successful accomplishment.

Mr. W. J. E. BINNIE congratulated the Author on the clear way in which the Paper was written. The work that it described was of great interest. The Author referred to the reasons for rejecting the proposal to lay the pipe-line on the surface of the river-bed, and gave as the first objection the danger of damage from anchors. There were many instances of pipes being laid on the bottom of a river where the bed was not liable to scour. A pipe had been laid from the island of Hong-Kong to the mainland, although in that situation the pipe was liable to be broken by ships dragging their anchors; the pipe was weighted down at intervals with large blocks, however, so that if one portion of the pipe happened to be broken by an anchor the damage would be localized. Mr. Binnie.

During the War his partner, Mr. Martin Deacon, M. Inst. C.E., had had to get a supply of water across a channel in connection with an aerodrome near Dymchurch, with as little delay as possible, and he had used an armoured hosepipe; before doing so he had made inquiries at Fleetwood, where ordinary armoured hosepipes had been used, one 12 inches in diameter and several smaller ones. Some of them had been in use for 30 years and were still in good condition. If a pipe had to be laid very quickly, or if there was no objection to its being laid above the bed, that method was very simple when a small pipe was used.

With regard to the velocity of the current, the great difficulty of keeping the trench open with a strong current was emphasized in the Paper. At Vancouver it had been necessary to lay pipes across the Narrows, about 1,300 feet in width; there was an 8½-knot tide, and it was impossible to open a trench. Each pipe was therefore dragged right across by means of a capstan situated on the farther bank. He believed that there were eleven pipes altogether, the older ones being 12 inches in diameter and the others 18 inches in diameter. In recent years some of the old pipes had been taken up after having been in position for more than 25 years; they were 12-inch pipes and were originally about 1 inch thick, and when they were removed it was found that at certain places the tops had been

Mr. Binnie. reduced to about $\frac{1}{2}$ inch, and even $\frac{3}{8}$ inch, by the scouring of the current.

The Author. The AUTHOR, in reply, expressed his appreciation of the kind remarks which the speakers had made about the Paper and about the work itself.

With regard to the external wrapping of the pipes, he agreed with Mr. Davidson that, were the work being done to-day, instead of hessian-wrapped pipes the more modern bitumen-sheathed type would be used. At the time when the pipes were purchased, however, hessian wrapping was the latest method, as Mr. Davidson had suggested. With regard to the hessian wrapping one curious thing had happened which was unique in his experience. He found one morning that a great deal of this wrapping had disappeared entirely from the pipes, and no trace of it could be found. A watch was therefore kept, and it was found that cows were allowed in the field where the pipes lay. The cows had a great liking for the hessian wrapping, and stripped it off by the yard.

A considerable quantity of Low Moor iron was used on the scheme in preference to steel, especially under water, but the flange-bolts, to which reference had been made, were very well protected against corrosion. They were not only galvanized, but were coated thickly with bitumen, in addition to the wrapping, and it was felt that, as neither water nor air could get to them, they were not likely to deteriorate in the course of time.

The methods of carrying a pipe-line across a river were almost unlimited in their variety, and the problem of the engineer was to originate or to adapt that method which best conformed with the local conditions. Apart from the actual physical conditions, there were other points which had to be considered, such as, for example, the effect which would be caused by any interruption of the supply. In the case described in the Paper, the pipe-line was the main channel for the water-supply of a city, and it was considered undesirable to run any more risk of interruption than was unavoidable. In some cases, however, the taking of certain risks might be justified, and a very much cheaper method could then be used.

In all probability the cheapest and quickest method of carrying a pipe-line across a river was to use steel pipes with welded joints, the pipes being assembled on the bank at right angles to the river. The pipes could be assembled either on free-running rollers or, in the case of a long pipe-line, on flat bogies running on a temporary light railway. Cables would then be attached to the leading end and taken across the river to winches on the opposite bank. During a period of slack water and absence of wind, the pipe-line would be hauled across and allowed to sink to the bed of the river. That

The Author.

method pre-supposed a combination of favourable conditions which were not often met with on one site. If the pipes were sunk by allowing water to enter them, great care was necessary, as the water tended to concentrate at the lowest point and might cause a sharp angle to form in the pipes, with consequent fracture. The method was not suitable for permanent work, where an interruption of the supply would have serious results. In one case in the United States a 22-inch gas-main had to be laid under the river Mississippi where the latter was 3,000 feet in width and 125 feet in depth, and it was divided into six smaller pipes on reaching the river-bank, so that some of them at least would remain in service in case of accident.

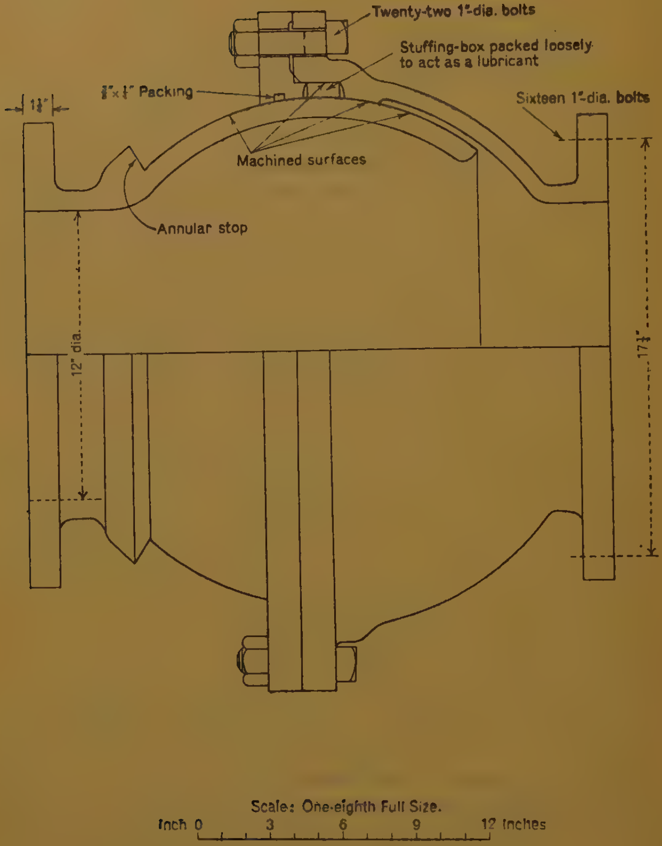
With regard to the method used for crossing the river Foyle, the Author had put various alternative proposals before the contractor, although he considered that the one actually used gave the greatest certainty of success in laying and of permanency in use. One alternative which was considered was to attach below the invert of each of the pipe-lines a 3-inch or 4-inch steel tube, fitted with nozzles, all pointing in the same direction, at intervals along the underside, through which it was intended to pump high-pressure water. It was considered that if the pipes were first lowered to the bed of the river and the nozzles then brought into operation, the sand would be washed away and the pipe-line would gradually sink to any desired depth The reason why that proposal was abandoned was that, especially on the north-west side of the river, the bed contained a number of large boulders, which would not have been removed by the jets. He was interested to know that a somewhat similar method had actually been used at an earlier date.

Both the "Victaulic" and the "Carlton" joints had been considered for providing the necessary flexibility in the pipe-line. He had often used the "Victaulic" joint, which was suitable for pipe-lines where only a small movement was anticipated. During the actual process of laying the submerged pipes at Londonderry, however, the movement required was as much as 25 degrees, and that could not be obtained with the "Victaulic" joint. The "Carlton" joint was a light and economical type of ball-and-socket joint with a considerable range of movement, but the type actually used (*Fig. 8*, p. 214) was adopted as its great strength enabled it to resist successfully the considerable stresses met with during the process of laying.

The concrete pipes used were centrifugally spun and were manufactured in England. The reinforcement assisted them to withstand the severe handling of the railway and shipping companies, but in spite of that reinforcement a large proportion of the pipes arrived in a damaged condition. The reinforcement was also required for the

The Author.

Fig. 8.



LONGITUDINAL SECTION OF CAST-STEEL BALL-AND-SOCKET JOINT.

pipes in the peat bog, which were carried on piles driven at 6 feet intervals, as described on p. 192. The Author.

The point had not been raised in the discussion, but a disadvantage of concrete pipes, as compared with iron or steel pipes, was that the inner surface "coated up" much more rapidly and, in consequence, the pipes had to be brushed out more frequently. This coating, or slime, if not regularly removed, tended to retain colour which, under certain conditions, such as excessive alkalinity of the water, might be released and thereby affect the supply. In comparing the cost of concrete and metal pipes for water-supply this question of brushing-out had to be taken into consideration.

Reference had been made to the weight of the pipe-line. The unusual thickness of the metal, together with the weight of the inner and outer coatings, caused the pipes to sink readily, even with the interior kept free from water. The temporary support given to the 100-feet lengths was not shown on Figs. 7, Plate 1; it was given only occasionally when there happened to be an unusually rapid current, and it was merely a temporary tie from the stern of one of the pontoons to the centre of the pipe-section.

The question of laying the second pipe-line in a separate trench had been given careful consideration. The labour-costs of laying two entirely separate lines would, however have been nearly double that of laying a twin pipe-line in a single trench. He thought that, in view of the depth at which the pipe-lines were laid, and the thickness of the mattress which was added, the danger from anchors was really very slight, and the strength of the pipes themselves was such that a fracture was unlikely. At the time, it was thought that the principal risk consisted in the possibility of a joint blowing out, and if that happened, the second pipe-line, although only four feet away, would not be seriously affected.

With regard to the concrete weight-blocks placed on the external bends, although bends of large radius under low pressure and with fixed joints might not require weighting, having regard to the comparatively high internal pressure of the Foyle pipes and also to the use of freely-moving ball-and-socket joints, the Author considered these weight-blocks to be essential. In the case of water-power schemes employing heads of up to 1,000 feet or more, steel anchor-rods and heavy concrete blocks were used at all bends, whether vertical or horizontal, to prevent any possible movement.

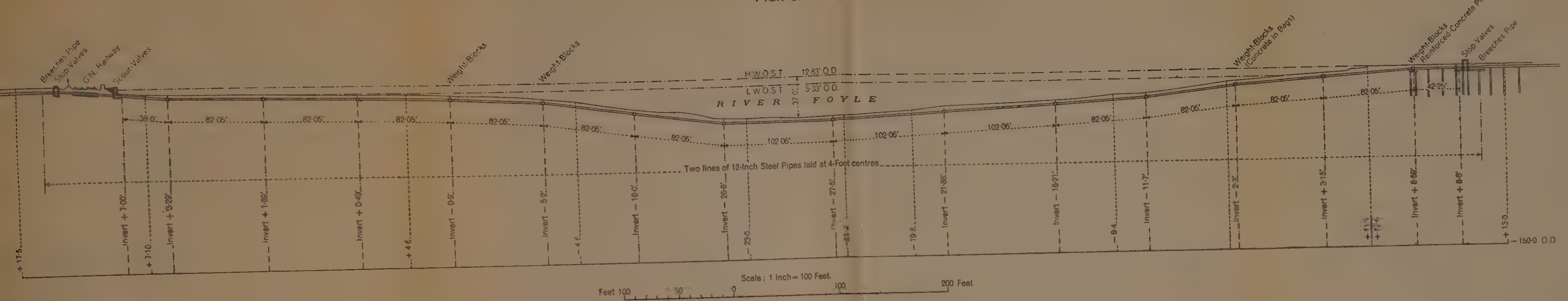
Although the surfaces of the ball and socket were very accurately machined and polished he did not think it advisable to rely on "contact" for watertightness, as under a head of 426 feet the

The Author. smallest jet would rapidly wear away the metal. The surfaces provided with an annular groove filled with grease packing meas $\frac{3}{8}$ inch by $\frac{1}{4}$ inch, and also with an annular stuffing-box packed lc to act as a lubricant, as shown in *Fig. 8.*

*** The Correspondence will be published later.—Sec. Inst.

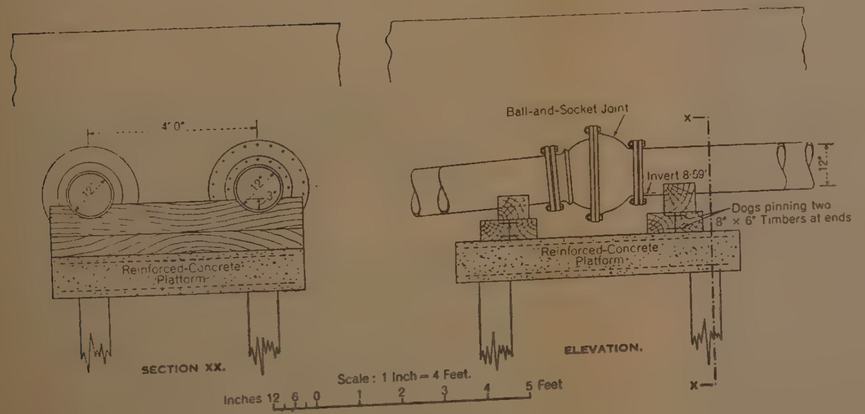
THE RIVER FOYLE CROSSING, (LONDONDERRY WATERWORKS).

FIG.: 3.



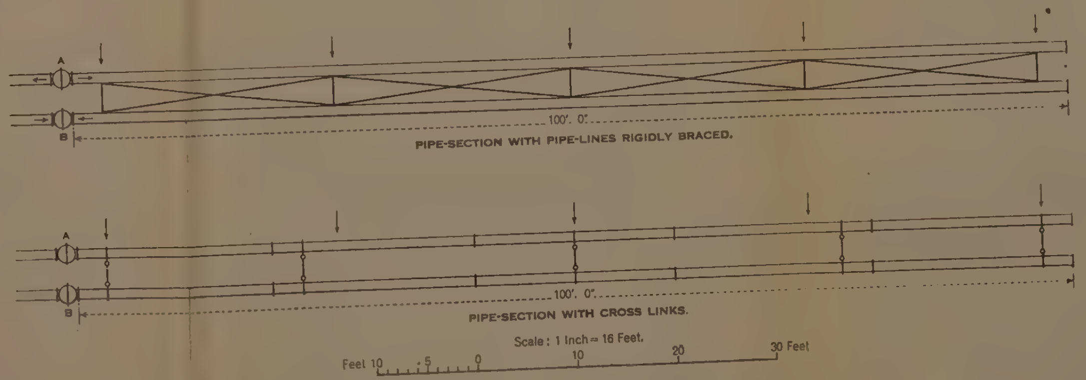
SECTION OF RIVER AT SITE OF CROSSING.

FIGS: 4.



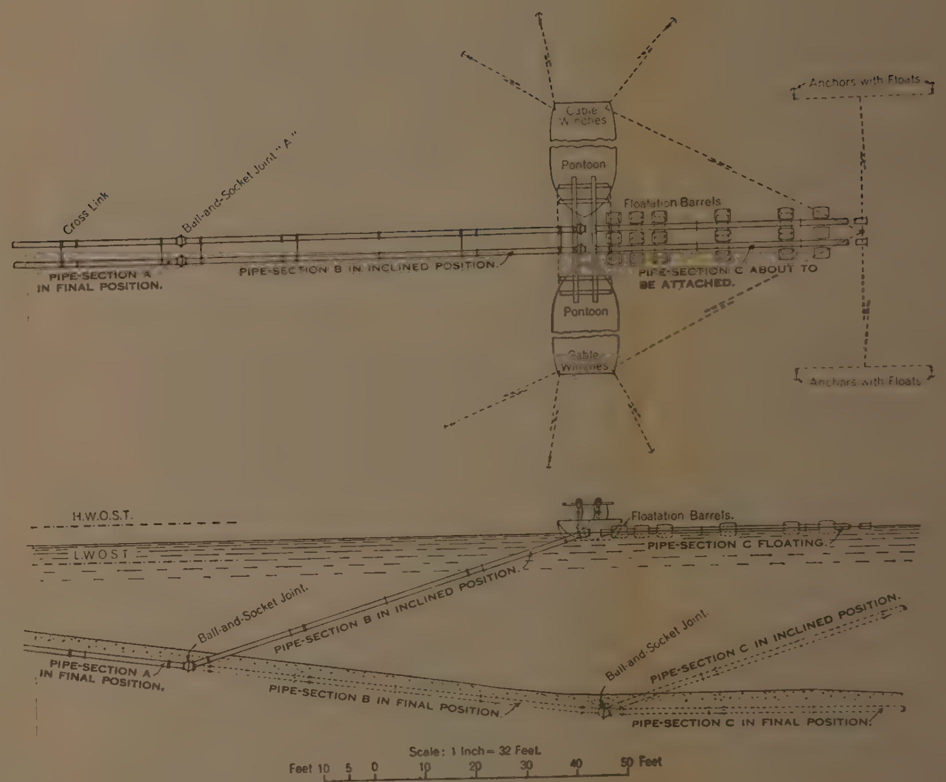
BALL-AND-SOCKET JOINTS, WITH SUPPORTS USED ON RIGHT BANK.

FIGS: 5.



METHODS OF CROSS-CONNECTING PIPE-SECTIONS.

FIGS: 7.



METHOD OF LOWERING PIPE-SECTIONS INTO POSITION.

W. CRISWELL.

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ORDINARY MEETING.

18 February, 1936.

Mr. JOHN DUNCAN WATSON, President, in the Chair.

The following Paper was submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Author.

"A General Comparison of Gas and Electricity for Heat-Production."

By Arthur Henry Barker, B.Sc., B.A., M. Inst. C.E.

TABLE OF CONTENTS.

Introduction.

An effort has been made in this Paper to state with accuracy the complicated facts which lead to a comparison of gas and electricity as agents for heat-production. Controversial opinions are excluded as far as possible; such as are expressed are personal to the Author, and are based on various data and observations. The origin of this information is in most cases indicated.

The Differences between Gas and Electricity.

The fundamental difference is that, while gas is a purified fuel which is readily transported to any point where heat is required, electricity is not really a fuel but is mobile energy. Both sources of heat are referred to as "agents" in the remainder of the Paper.

In the manufacture of gas it may be said that the solidity, ashes and smoke, as well as most of the labour involved in the use of coal, have been eliminated, leaving only the combustion and its

normally innocuous products to be dealt with by the consumer. The price of this purification consists of the manufacturing costs and some 20 per cent. of the energy of the coal, leaving (assuming all the coke and other by-products are turned into gas) a potential 80 per cent. available for use by the consumer.

In the production of electricity the purification of the fuel is carried a stage further. Not only are all the material and chemical characteristics of the fuel eliminated, but the necessity for its combustion and the labour so involved are also removed. Of the energy originally contained in the fuel, some 20 or 25 per cent. is now available, the remainder having been sacrificed in the transformation. The capital charges and costs of generation are also relatively high.

There are clearly cases where, as far as utility is concerned, this costly further stage of purification is a waste of money. In other cases, however, it has, for various reasons, a value to the consumer far in excess of its cost.

This difference between the two agents has two outstanding results:

(1) Before its energy can be used as heat at the desired point, gas has to undergo the process of combustion with its attendant disadvantages, namely, high temperature, and products of combustion, which have to be removed.

(2) The use of gas consumes much less fuel than electricity, and the gross heat derived from it is therefore potentially and actually considerably cheaper. The relative cost of the net heat usefully employed varies in different cases, the reasons for which will be discussed later.

First Cost.

The cost of an electric supply-station appears to be about three times that of a gas-works of equivalent output of energy; that is, from £70 to £200 per 1,000 therms capacity per annum for gas, and from £180 to £600 for an equivalent amount of electricity; these figures, however, vary according to the size of the plant.

Capital Cost of Distribution.

Although it is not possible to give an accurate general statement of the relative transmission-costs (which vary greatly according to the method and purpose of the distribution and the nature of the country), a gas-main generally costs from three to five times as much as a corresponding buried electric cable, and from ten to twelve times as much as electric cables suspended overhead; namely, from £4,000 to £6,000 per mile for gas-mains, as compared with £800 to £1,800 for underground, and £280 to £500 for overhead electric cables.

The great cost of electrical substations, where these are necessary, has no parallel in the case of a gas undertaking. The cost of these substations cannot be estimated per 100,000 B.Th.U. of output, and must be included in the cost of the supply-stations.

Equipment of Buildings.

The cost of equipping buildings for the use of electrical power is, in the experience of the Author, usually from three to five times that of an equivalent system of gas-pipes, but varies greatly according to the character and purpose of the installation.

Cost of Production.

TABLE I.—COST OF PRODUCTION OF GAS AND ELECTRICITY PER 100,000 B.TH.U.

	GAS. Pence per 100,000 B.Th.U.*	ELECTRICITY. Pence per:	
		100,000 B.Th.U.	Unit.
For Production of Gas:			
Overall cost of coal . 5·2*d.*			
Less residuals . . 3·4*d.*			
Balance . . 1·8*d.*			
Net cost of coal	1·8	2·930	0·10
Purification and stores . . .	0·1	0·293	0·01
Salaries and wages, and management	0·7	1·460	0·05
Repairs to plant	1·5	1·750	0·06
Net cost as supplied to gasholder or mains	4·1	6·433	0·22
Interest and depreciation on capital, etc.	2·0	3·000	0·103
Gross cost at works .	6·1	9·433	0·323

* 1 Therm.

The figures in Table I have been summarized from published information supplied by the industries concerned, or from the general experience of the Author. The actual costs in any specified case are liable to vary so widely that general applicability of any such figures should not be assumed. They are intended only to give a general idea of the usual relative costs. They appear to show that, while the cost of generating a given energy-output is some 50 per cent. greater in the case of electricity than in the case of gas, the capital charges on the cost of electric cables are from one-fifth to one-tenth of those incurred in the distribution of an equivalent amount of gas.

Overall Thermal Efficiency of Production.

It is generally true that the generation of electrical power from coal, by the methods in use at the present time, involves the complete loss of about 75 or 80 per cent. of the total energy in the fuel, only about 20 or 25 per cent. being converted into electrical power.

The figures for the production of gas are approximately the reverse of these, the process of conversion transforming 75 or 80 per cent. of the energy in the fuel and discharging the remainder to waste. This figure is arrived at by taking into consideration the thermal value of all the by-products of gas, such as coke and gas-tar.

Main Difference.

The principal difference between a gas-works and a power-station is that while the latter is designed to produce electric power alone, the former produces, in addition to gas, a number of by-products and residuals which are of commercial value.

Appearance.

The difference in appearance is very noticeable; for example, the Battersea power-station may be contrasted with the Fulham gas-works, or the Aldershot gas-works as seen from the Hog's Back. The psychological effect of such contrasts on the public may be very great. On the other hand, the appearance of electric pylons and cables sprawling over an otherwise beautiful countryside does not increase any popular liking for electricity.

Equivalents.

The equivalents of heat, in the form of therms of gas and units of electricity respectively, are set out to scale on the vertical ordinates of *Figs. 1.* Thus, 1 unit = 0·0342 therm, or 1 therm is the equivalent of 29·3 units; alternatively, 1*d.* per unit for electricity is the same price as 29·3*d.* per therm.

Charging-Rates.

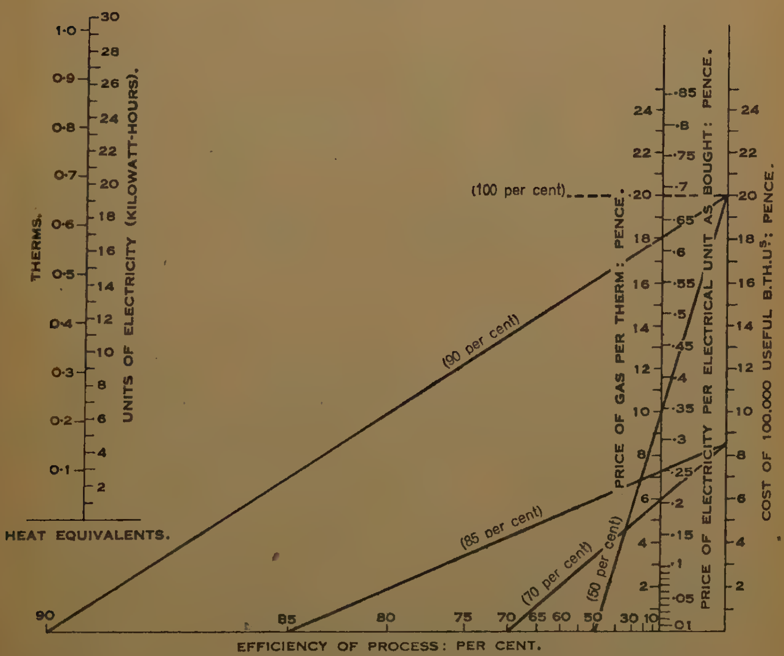
Until recent months the rate of charging for a gas-supply has been usually constant at the rate of so much per therm, irrespective of the annual consumption. With electricity, special rates have been devised whereby a fixed annual charge is made for the supply, based on the floor-space, the rateable value or the total loading, with a low rate per unit actually consumed. The effect of this method of charging is that the greater the total consumption, the lower the net cost per unit. Thus with a fixed charge of £5 and ½*d.* per unit the cost if 250 units were used per annum would be equivalent to 155*d.* per therm, while if 5,000 units were used per annum the cost would

be the equivalent of 21·6*d*. It is thus impossible to calculate either the actual cost per unit or the relative costs per therm without information as to the total consumption per annum. It is open to discussion whether any proportionate share of the fixed charge should be debited to the cost of electrically-derived heat, having regard to the consideration that the fixed charge would, in any case, be required for the lighting-service.

Features of Electricity as a Heating Agent.

Apart from its relatively high cost and the inevitable dangers attached to its use, electrical energy, if it could be supplied at any

Figs. 1.



time in unlimited but controllable quantity, would be almost an ideal means for the production of any kind of heat. By its agency pure heat-energy can be delivered through flexible wires in any quantity, at any temperature, and in any desired form (convective or radiant, luminous or non-luminous, of any desired wavelength), without any kind of labour, trouble or difficulty, to any accessible point in space.

There is no other source of heat which, at any moment, can be immediately and directly supplied to the consumer at any point where required, at any desired rate and temperature, and generally with almost 100 per cent. efficiency. Further, it does not need any intermediate heat-carrying medium, there are no products of combustion, no stand-by losses, practically no absorption-coefficient, and only a very small time-lag. Electricity can be rapidly cut off, when not required, by the simple and almost frictionless mechanical movement of a switch, which may be readily operated automatically by a simple and reliable form of thermostat.

Disadvantages of Electrically-Derived Heat.

(1) The amount which can be supplied is rigidly limited by the capacity of the generating-plant and cables. If the connected load is greater than the cables or the generating-plant can supply, there is always the possibility of a sudden peak-load occurring which will give rise to grave difficulties. These disadvantages can be minimized, however, by means which need not now be discussed.

(2) The rate of supply cannot usually be regulated continuously from zero to maximum power (although this is sometimes possible in particular kinds of apparatus), but only by a series of steps. Frequently, it can only be effectively controlled by switching the full power on or off for a longer or shorter period of time. The amount of heat obtainable from one fitting cannot by any means be increased temporarily beyond the calculated amount, although supplementary fittings may be easily connected.

(3) The use of energy in this form involves the use simultaneously of complicated and expensive plant and organization, which are liable to breakdown, and the power must be generated *pro rata* with its use.

(4) If the source of power breaks down for any reason, even for so normal a cause as the operation of a circuit-breaker, the supply of heat is promptly stopped and cannot be restarted until the complicated generating plant is restored to working order, or until the cause of the breakdown is removed. This feature sometimes gives rise to very serious difficulties, and the whole life of the community may be temporarily paralysed.

(5) Its use involves certain physical dangers to life and property, which, however, apart from accidents, are negligible if the apparatus is in good order and is properly designed and used.

(6) There exists no means whereby the energy can be stored in any useful quantity, except as heat at relatively low temperatures in large masses of heat-absorbing material, such as hot water or oil

contained in large cylinders, the accommodation of which is inconvenient and expensive. The use of these is wasteful and the time-lag great. Some of the most valuable properties of electricity, such as its mobility, its instantaneous control, and the absence of time-lag, absorption and loss in transit, as well as the simplicity of the system of conveyance and distribution by flexible leads, are lost if large storage-reservoirs are used.

Comparison with other Agents.

The use of any other agent, including gas, gives rise, along with the heat, to the emission of products of combustion which are mainly of a deleterious character, and are at a high temperature; these products are, in many cases, difficult to deal with in a satisfactory manner.

It is only in certain cases that heat derived directly from the combustion of actual fuels (such as gas) can be employed without the use of chimneys, or their equivalent, and (where a low or moderate temperature is desired) without some absorbing and heat-carrying medium, such as water. The latter method has several disadvantages, but the heat may be transferred from the products of combustion to the water, with the result that the temperature at which the heat is available is reduced to a usable value.

Features of Gas as a Heating Agent.

Of the fuels just considered, gas has to a certain extent some of the same valuable properties as electricity, but as it is not purified to the same extent it has some inevitable drawbacks which electrical power does not possess. Its principal advantages are:

(1) That its production consumes much less fuel than is necessary for the generation of a corresponding amount of electrical energy.

(2) That it can always be regulated exactly to the requirements.

(3) That, owing to the fact that it can be stored in great quantity, a large temporary increase in consumption is possible in order to meet an emergency or overload.

(4) That, although serious breakdown is by no means unknown, it is less probable than with the more complicated electrical plant.

(5) That in some cases the products, which are innocuous if complete combustion is effected, can be allowed to mix with the air heated as a diluent, and so secure, in a certain sense, an efficiency of 100 per cent.

Disadvantages of Gas.

(1) It needs to be ignited and to be supplied with air before the heat can be developed.

(2) It is odorous and dangerous if it escapes unburnt, or is incompletely burnt. Mixed with air it is highly explosive as well as poisonous.

(3) Its combustion gives off gaseous products of combustion which have to be removed; this is not always easy without incurring expense and a great loss of efficiency.

(4) If the maximum efficiency is aimed at, condensation of the water vapour contained in the products is necessary, and this forms a corrosive liquid which attacks almost every kind of metal, and which has to be carried to a drain.

(5) Control of the temperature at which the heat is generated is impossible without a sacrifice of efficiency. Heat cannot be delivered at a relatively low temperature without either using an absorbing medium or diluting the products.

(6) It needs attention to ensure that the burners are in good order and that the combustion is perfect.

Relative Danger.

It must be recognized that the use of any source of concentrated energy involves some degree of danger, especially when the energy is as easily convertible into other forms of energy as is that of gas or electricity.

Gas.

The dangers of gas are its liability to escape, its poisonous character, its explosiveness when mixed with air, and the high temperature at which the heat is necessarily generated, which thus involves risk of fire. Escapes may be due to defective piping, to lighted burners being accidentally extinguished, or to a tap being accidentally turned on. Buried pipes conveying gas are occasionally liable to underground corrosion or fracture. The gas thus liberated underground may travel a considerable distance in the substance of the road-material, giving rise to explosions in houses unconnected to the mains, and even poisoning persons residing in such houses.

Processes are known by which coal-gas can be rendered non-poisonous. It is surprising that these have not received the attention of the gas-industry or of the legislature. There is no greater deter-

rent to the general use of gas than its poisonous character, due to its carbon-monoxide content.

Electricity.

The danger in the use of electricity is principally that of touching accidentally, or in ignorance, an exposed live conductor, which may result in the instant death of the person involved if his earth contact is good. Another risk is due to defective insulation causing a short-circuit or other defect, and thus giving rise to danger of fire. If electrically-generated heat cannot escape, it will accumulate until very high temperatures are reached; fire or an explosion may then be caused.

Most of such dangers can be guarded against by adequate care in the design, erection and supervision of the installation, by supplying adequate and carefully-located circuit-breakers and earthing-conductors, and by subsequent inspection. The dangers only become imminent when the construction is cheap and inferior in quality. The principal inconvenience met with in the use of electricity is its liability to breakdown. Such breakdowns may cause serious inconvenience and loss; it is only rarely that such inconvenience is prolonged, but when it arises its effect is widespread and has assigned to it a significance out of proportion to its real importance. Generally, however, such a breakdown is nothing more than a nuisance.

A general comparison of the relative dangers arising from the use of the two agents may perhaps be made from the figures in Table II, taken from the annually published Report of the Registrar General for the year 1934.

TABLE II.

Fatal Accidents.	Gas.	Electricity.
Suicides	1,853	—
Accidental deaths	141	67
Deaths per million excluding suicides	3·35	1·6

As, however, the number of existing gas installations in the country is probably more than twice the number of electrical installations, it would appear that the accident-rate of the two is about equal. The question of suicides is inappropriate for present discussion; this drawback to the use of gas would be eliminated if gas were made non-poisonous by the conversion of the carbon-monoxide content into a non-poisonous compound. A combustible gas could probably never be made non-explosive.

Comparison between Gas and Electricity in Various Applications.

Either of these two agents can be used to produce heat for many different purposes. It is intended in this Paper to estimate as far as possible their relative value in their most important uses, such as:—

(1) Lighting.
(2) Water-heating.
(3) Space-heating of buildings.
(4) Cooking.
(5) Furnace-work.
(6) Welding, and local intensive applications.

Principles of Comparison.

In each case comparisons can be made from many different aspects. If data were available, every such comparison should be made in reference to the "total cost"; that, however, would have to comprise not only the direct cost of the agent itself and of the labour involved in its use, but also the interest and depreciation on the first cost of the necessary plant, and the monetary values, positive and negative, as far as they can be estimated, of the various advantages and disadvantages of each of the agents when used for the particular purpose under discussion. In attempting to include all such matters in terms of "total cost," serious practical difficulties and uncertainties are involved, on account of essential differences between the two agents, which in some cases make accurate comparison impossible.

Control.

The amount, and therefore the cost, of any agent used in actual service for a particular duty depends not only upon its potential technical efficiency but also on the ease with which in practical use it can be conserved by careful, or wasted by careless, use. For example, owing to the accessibility of the switch near the door an electric light would usually be switched off by a normally careful person every time he left the room, even for a brief interval. A gas light, on the other hand, would not usually be extinguished on such occasions, as it would be seldom controllable from the doorway, the provision of a distant-control self-igniting gas-switch being both expensive and inconvenient. In the course of a year the saving due to switching off for those short periods would be marked. On the other hand, the ability to regulate the gas light from a very low to a high value enables gas to be economized, a facility which does not exist with the electric light without expensive provision. Thus, although gas lighting might,

by calculation, appear much cheaper than the same amount of electric light, the comparison in practice might be very different (although it is impossible to say by how much) owing to easier control of the electric light or to the possibility of regulation of the gas lighting. Similar differences arise in many cases, which affect the relative costs in a greater or less degree, and which may or may not be susceptible to calculation.

Carrier-Current Control.

The facilities for the control of electricity and gas respectively, in wider application than to individual units, are of importance. A practical system of distant control of electrical appliances has been recently developed whereby alternating currents of periodicity different from that of the main supply can be superimposed on the main current in the cable. Any individual power-using unit connected to the supply can be put under the control of a specially-tuned sensitive relay-switch, which will automatically switch the main supply on or off when it receives " carrier currents " of the special periodicities to which it is tuned, and which will not respond to currents of any other periodicity. This enables the supply company's control-room to switch on or off all the power-using units supplied with relays tuned to particular periodicities; as there is practically no limit to the number of periodicities which can be employed, different classes of units can be independently controlled.

There are of course many services, such as lighting, incandescent heating and power, to which the supply must be continuous, but there are also many others, such as non-incandescent heating and hot-water supply, a temporary interruption of which would be unnoticed by the users. In addition, there are other services, such as street lighting, which are not required during certain hours; the switching off of these effects a considerable economy.

This facility enables a supply company to tide over periods of peak-load which only persist for half an hour or so; as the costs of the supply company depend largely on the magnitude of such peaks it enables current to be supplied for purposes for which absolute continuity is not imperative at a much lower cost than would otherwise be possible. Gas in its nature is not susceptible to anything resembling this system of control, although unsuccessful attempts have been made to control burners by pulses of pressure sent along the mains.

Electric street lighting can by this method be controlled from the centre. More or less light can be turned on as required, with an ease of control which cannot be attained with gas lighting and which would therefore vitally affect relative costs.

Industrial Plant.

Similar cases occur in industrial applications. The properties of certain heating agents may make operatives less efficient and so increase the cost of work, or may affect the total cost in other ways, and the monetary value of such effects may be difficult or impossible to assess. Thus figures derived solely from the cost of the fuel and the calculated efficiency of its utilization do not answer the practical question " What is the cost comparison between these two in actual use ? ", but only the question " What would be the cost comparison if both were carefully used in such ways as to produce identical results ? " It is usually difficult to arrive at identity of result, and the operation requires great care. If comparisons are made without such care the results are indeterminate and therefore without value, and if care is taken the comparisons are apt to become unpractical.

Where such comparisons have been made in such a way as to be both practical and reliable—and there are some such cases—the results may sometimes be summarized by giving the relative costs of gas per therm and of electricity per unit at which the running costs, either taken over an entire installation or when used for particular purposes, would in normal circumstances be approximately the same.

This is only one example of the immense difficulties involved in the attempt to reduce to a practical money-equivalent all the advantages and disadvantages of different ways of doing the same thing. To make such a comparison in any other way, however, leads to an indeterminate or a misleading result. In some cases it is only possible to describe the respective advantages and the calculated fuel-costs, and to leave to the purchaser the task of assessing whether these differences are to him worth the additional cost of the better of the two.

EFFICIENCY.

The observed cost is always a direct function of the " efficiency." The difficulty of defining the meaning of the latter expression, in order that the result may be of some practical service, is, in some cases, very great. Generally, it is applied to the ratio of the energy physically necessary to perform an operation to that contained in the fuel actually used. This elementary definition is often inadequate and needs for practical purposes to be supplemented by explanatory conditions and reservations, and it will be necessary, in each case, to define exactly what is meant by "efficiency." In the remaining portion of the Paper it is almost always used in a special sense, determined in each case by the type of apparatus and

by the object of the calculation. Its meaning will frequently be very different from its usual significance, as represented by the expression :—

$$(\text{Total amount of heat spent}) \times (\text{Efficiency}) = \text{Heat physically necessary},$$

or, in other words :—

$$\frac{\text{Heat physically necessary}}{\text{Efficiency}} = \text{Total heat paid for.}$$

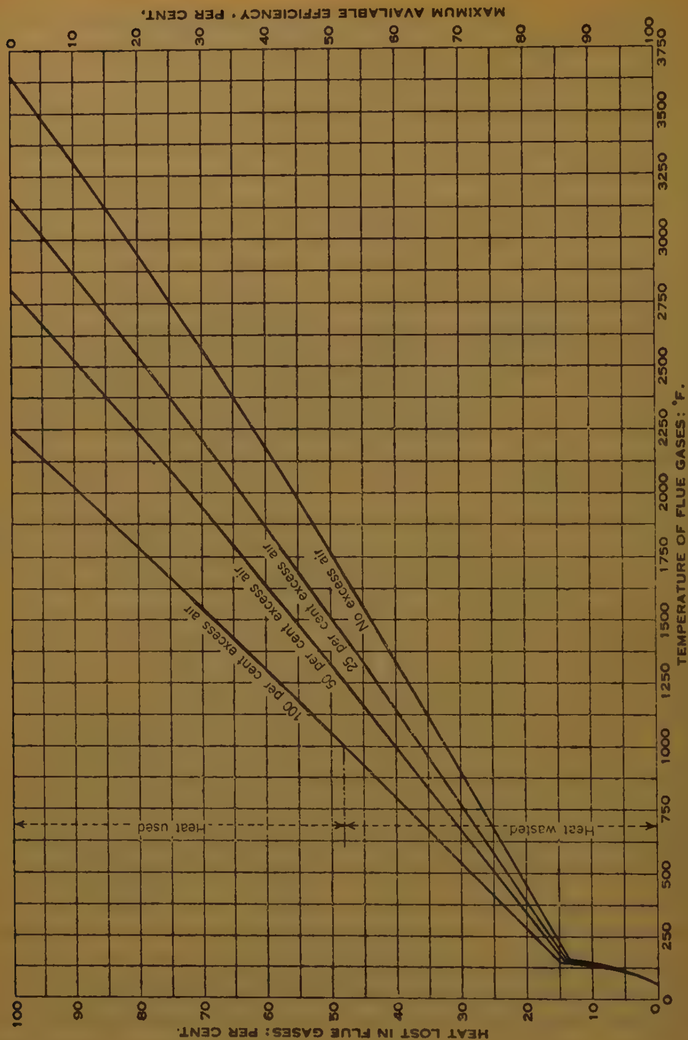
Differences between Gas and Electricity in respect of Efficiency.

One fundamental difference between the two agents is that, with gas, the continuous evacuation of the products of combustion necessarily removes to waste a considerable proportion of the heat generated by the combustion. The efficiency is thereby reduced accordingly. This loss does not exist in the case of corresponding electrical apparatus.

The minimum loss will be seen from *Fig. 2* (p. 230), which shows the percentage of the total heat in the products at different temperatures for gas of one particular composition. This varies according to the excess air used in the combustion. This diagram is theoretical only, as a considerable amount of heat is always lost by radiation from the flame. The amount so lost is uncertain. The effect of this loss is that the gross input cannot be entirely accounted for in the flue-gases. Further, at high temperatures some heat is absorbed in the dissociation of the carbon dioxide and water-vapour that is produced by combustion. For these two reasons the theoretical flue-temperatures in the upper ranges are from 300 to 500° F. above those obtainable in practice. This fact must be borne in mind in attempting any accurate calculation based on this diagram.

Usually about 10 per cent. of the total heat is the latent heat in the water-vapour that is generated by the combustion of the hydrogen constituent of the gas. If the temperature is not reduced below 212° F. all the vapour passes away with the products, and carries its latent heat with it. The maximum possible efficiency of a gas-heated appliance cannot, therefore, in any case exceed 90 per cent. unless the gases are cooled by passing them over large surfaces maintained at a temperature considerably below 212° F. This is not a practical operation. Thus, for instance, if any gas-appliance evacuates the products of combustion at a temperature of 1,000° F. with 100 per cent. excess air, its efficiency cannot exceed about 52 per cent., since about 48 per cent. of the total heat of the gas would be carried away in the products of combustion. In certain cases some of this heat can be recovered by regeneration, but not in all.

Fig. 2.



PROPORTION OF TOTAL HEAT OF COAL-GAS LOST IN PRODUCTS OF COMBUSTION.

Cost.

In accordance with the definition on p. 228, the true cost in pence of the fuels alone for any process is as follows :—

For electricity :—

$$\frac{\text{Heat physically necessary}}{\text{Efficiency of process when using electric power}} \times \frac{1}{3{,}416}$$

$$\times \text{ (Cost of electricity in pence per unit).}$$

For gas for the same process :—

$$\frac{\text{Heat physically necessary}}{\text{Efficiency when using gas}} \times \frac{1}{100{,}000} \times \frac{\text{Pence per therm}}{1}.$$

The relative cost is therefore

$$\frac{29\cdot4}{1} \times \frac{\text{pence per unit}}{\text{pence per therm}} \times \frac{\text{efficiency (gas)}}{\text{efficiency (electricity)}}.$$

In this formula only the bare cost of the fuel is considered, and the expression is therefore liable to be criticized as unpractical ; neither the value of the possible relative advantages and disadvantages, nor any other consideration than the bare cost of the fuel, however, comes into the question except in cases where these factors can be incorporated in the " efficiency " itself.

Fig. 1 is designed to enable comparisons of fuel-cost to be readily made, when only the cost per unit and the efficiency of the process (on whatever basis that expression is defined) are known. The principle of this diagram is that of the formula :—

$$\frac{\text{Heat physically necessary}}{\text{Efficiency of process}} = \text{Heat used.}$$

Applied to cost, this is

$$\frac{\text{Price of 1 therm}}{\text{Efficiency}} = \text{cost of 1 useful therm; or alternatively}$$

$$\frac{\text{Price of 1 electrical unit}}{\text{Efficiency}} \times \frac{100{,}000}{3{,}416} = \text{cost of 1 useful therm.}$$

Fig. 1 applies in all cases where the efficiency can be defined in such a sense that it is applicable in principle to the above relation.

Efficiency from Cold and in Steady State.

There are two kinds of efficiency ; (*a*) that referring to the case where the apparatus is assumed to start from cold to perform one specific operation, and (*b*) where the operation is continuous. For instance, it may be assumed that an oven is to be tested by heating a vessel containing cold water. For determining the first type of efficiency the oven would be cold at starting, and when the measurement is made the whole consumption would be observed from the time of starting the supply of heat until the vessel and water had been heated to the prescribed degree. A comparison with the heat given to the water would give the " efficiency from cold." If, however, the oven is first made hot, any number of such vessels can be heated up in succession before the oven is allowed to cool, the comparison

being observed between the rate of heating the water and the fuel-consumption. The efficiency determined in this way will be termed the "steady-state efficiency." In some cases the absolute value of the efficiency depends so much on the conditions that the figure is of very doubtful significance.

Empirical Efficiency.

In some such cases it is possible to devise an empirical definition by assuming an arbitrary value of 100 per cent. for electricity when used in a particular way, and then making a direct comparison with gas used in a similar way under the same conditions in the same apparatus. Thus, in the case of a furnace used for heating a comparatively small article, and served alternatively by electrical elements or gas flames inside the furnace, the absolute value of the efficiency depends on the article treated. In the former case the furnace would be wholly sealed from the outer air so that there would be no direct escape of heat by convection from the interior to the exterior. With gas it is necessary to provide a continual stream of air for maintaining the combustion and thus much heat is lost by convection, as the products carry away with them their heat-contents at a high temperature, approximately equal to that of the furnace. The "efficiency" is therefore relatively low and varies both with the combustion and the amount of excess air. The result is that more heat is required from gas than from electricity to produce the same result. The absolute value determined by experiment would, in either case, be of doubtful significance, depending on the size and character of the object heated; by varying the latter the apparent value can be caused to vary over a very wide range. The ratio between the efficiencies could be determined with some accuracy by the process described above.

The theoretical efficiency in such a case may be determined as follows:—

(*a*) (1) *Efficiency from Cold.*

Let H_G and H_E denote the heat delivered in the heating agent (i) during the experiment, (ii) per hour.

,, P denote the heat required to raise the structure of the furnace to the temperature required for the heating process.

,, Q ,, heat-loss transmitted by conduction to the outside of the furnace and afterwards lost to the surrounding air by convection and radiation (i) during the experiment, (ii) per hour.

Let R denote the loss of heat by interchange of the gaseous contents of the furnace, (i) during the experiment, (ii) per hour.
,, S ,, heat usefully employed in heating up the material.

The value of S is usually very small in comparison with the other quantities. P and Q are assumed to be the same for both agents.

Then using gas, $H_G = P + Q + R + S$
and using electricity, $H_E = P + Q + S$, since $R = 0$.

(2) *Theoretical Efficiency from Cold, using Values* (i).

With gas, $\frac{S}{H_G} = \frac{H_G - (P + Q + R)}{H_G} = 1 - \frac{P + Q + R}{H_G}$.

With electricity, $\frac{S}{H_E} = \frac{H_E - (P + Q)}{H_E} = 1 - \frac{P + Q}{H_E}$.

(*b*) *Theoretical Steady-State Efficiency, using Values* (ii).

Here $P = 0$, and H, Q, R and S are estimated per hour and not over the whole range of the experiment.

Efficiency with gas, $\frac{S}{H_G} = \frac{H_G - (Q + R)}{H_G} = 1 - \frac{Q + R}{H_G}$.

But with electricity, $R = 0$, and therefore the efficiency with electricity is $\frac{S}{H_E} = \frac{H_E - Q}{H_E} = 1 - \frac{Q}{H_E}$.

If in an electric oven R is zero, then

$$H_E = Q + S$$

where Q represents an inevitable loss, of magnitude varying with the temperature.

If it is assumed that the "work done" is $(Q + S)$ instead of S, the efficiency of the electric oven is $\frac{Q + S}{H}$ or 100 per cent. Further, if the article is very small where $S = 0$, $\frac{Q}{H} = 100$ per cent.

The value of Q for any temperature may be determined accurately by observing the number of watts required to maintain the temperature.

In the case of a gas oven, with the same reasoning the efficiency would be

$$\frac{H_G - R}{H_G} \quad \text{or} \quad \frac{Q + S}{H_G} = 1 - \frac{R}{H_G}.$$

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The value of H_G can be determined by observing the hourly consumption of gas.

The minimum value of R can be determined by calculating the proportion of the gross heat of the gas carried away by the products at the temperature of the furnace. This is shown in *Fig. 2*.

Thus if S is small a rough comparison can be made between the respective efficiencies by observing the hourly amounts of electricity and gas respectively required to maintain the same "effective" temperature in the empty furnace. This would not give the efficiency of either heating agent in a scientific sense, but a comparison between the two results would give their comparative values if the effective temperatures can be equalized; the proportion would, on certain approximate assumptions, be near to that of the true efficiencies. This convention is chiefly useful in the case of ovens and furnaces of other types, but the principle is of very general application.

It should be clearly understood, therefore, that the essential efficiency is not inherent in the agent alone but in the agent and in the apparatus, as well as in the use to which it is put and in the way in which it is used. An alteration in any of these factors alters the whole result. Thus the question whether, for a given purpose, gas or electricity will be the cheaper is incapable of a general answer, even when the cost of the heat is known.

It is a fallacy to assume that the relative cost is determined by the respective prices paid for the heat, or even by those prices with the academic efficiency taken into account, unless that value really applies to the case without modification (which it rarely does). On the other hand, it is equally fallacious to claim, as is sometimes done, an economy for a high-priced heating agent, such as electrical power, unless there is some definite reason why its high price is counterbalanced by some substantial saving. Claims for economy by the use of a high-priced heat can only be established if the savings in efficiency, capital charges on first cost, and builder's work, labour, control and convenience are jointly greater than the difference in the costs of the two sources of heat. For instance, in such a simple case as heating a large mass of water by direct electrical power, or in the continuous heating of a large building, little labour and no "diversity" are involved. Apart from capital charges, therefore, the cost in such a case is always proportional to the price of the heat divided by the efficiency. On the other hand, the facility with which the power can be shut off when required, and various other features, make electricity the most economical of all fuels for certain purposes when the "diversity" is great.

Frequently, a practical comparison for any particular installation can only be obtained by actual use. The result depends on such

factors as the user, whether the use of one fuel conduces to waste more than the use of another, or whether, owing to superior methods of control one is more readily economized than the other. In such a case, a reliable comparison between the heating agents can be made over an extended period in the same apparatus when used by the same person, care being taken that the same work is done by each agent; it is a difficult matter to ensure such uniformity. The comparison resulting from such a trial will vary when different apparatus is tested by this method. Large-scale observations on the total consumption of a large community, although interesting as giving an average result, can lead to no specific conclusion, and may be most misleading if used for calculating relative costs in particular cases, as for instance for determining whether an all-electric or an all-gas installation would be more economical.

Thermodynamic use of Electrical Power. Efficiencies Higher than 100 per cent.

The ease with which electrical energy can be turned into mechanical power renders possible developments in its use for certain heating-purposes at relatively low temperatures, which have been so little developed that they need not be fully discussed here. It is possible by the reversed use of a plant on the principle of a refrigerator to obtain heat from electricity at an efficiency far greater than 100 per cent. Thus in the warming of a swimming bath or in the raising of the temperature of a large mass of water by a small amount, it is possible, by suitable design, to attain an efficiency as high as 500 per cent. This is done by putting into the water energy in the form of low-temperature heat which is five times as great as that in the electrical current consumed in the process. There is no infringement of the principle of the conservation of energy in this process, as the heat itself is obtained from the surroundings and is raised in temperature by compression. The practicability of this process is only limited by the high cost of the plant required to work it, on which the capital charges would normally be so great that the cost of the electrical energy necessary would generally be dwarfed. For thermodynamic reasons it is only economically applicable where the temperature to be obtained is relatively low. Apart from its capital cost it is a conceivable future development for the warming of buildings.

Lighting.

The comparison of costs is complicated by more serious difficulties in the case of lighting than in any other case where either gas or electricity may be used.

The differences in practical use between them may be briefly summarized as follows :—

(1) Electricity "burns" automatically when switched on. Gas has to be ignited and kept supplied with air.

(2) Gas emits products of combustion which, although innocuous when combustion is complete, are otherwise obnoxious; they are debatably claimed to have a germicidal effect and to be more advantageous than deleterious. An electric light does not emit such products.

(3) An electric light, being completely shielded by the globe from contact with air or any surrounding objects, does not raise the air surrounding it to a high temperature; it can therefore be fixed almost anywhere with reasonable safety. A gas light generates a very high temperature and so cannot with safety be fixed near anything inflammable unless suitable precautions are taken.

(4) An electric light emits much less heat and creates less dirt; in consequence it can be fixed, focussed or reflected on the exact spot required much more easily than can a gas light.

(5) An electric-light bulb can be renewed or changed in power in a few seconds by replacing the bulb. Changing a gas-mantle, though cheaper, is more complicated and troublesome. A gas-mantle is much more easily broken than an electric-light bulb.

(6) More attention is required to keep a gas burner in order than is necessary with an electric lamp. The former has to be periodically blown clear of dust.

(7) An electric-light lead is flexible and the light can therefore be fixed at practically any accessible point. A gas-pipe is much less flexible or adaptable, and it can be carried only to places where there is no danger of fire, where there is easy access for air and dissipation of products, and where the burner can be readily reached for purposes of ignition, cleaning and other attention.

(8) An electric light can be operated from a distant switch fixed at any convenient point, but a gas light can only be so operated by the use of artificial and expensive means, such as pilot-lights or electric ignition. The regulation of a gas light is, however, continuous from zero to maximum power.

(9) A gas light at usual prices is substantially cheaper in fuel than an equivalent electric light of the ordinary type at present in use. [See Table V, p. 243.]

(10) The light from a good gas burner is softer and more pleasant to the eyes than that of an electric light of equal candle-power.

In the main these comparisons, especially those of convenience, show a definite advantage to the electric light for ordinary buildings where economy is not of paramount importance; so much so, in fact, as in most cases to counterbalance the relative cheapness of gas.

Exceptional cases are :

(*a*) Houses where economy is more important than convenience.

(*b*) In street and factory lighting, where the products of combustion are not of consequence.

(*c*) Where the lighting-units can be fixed in positions enabling ignition and the necessary attention to be easily performed.

(*d*) Where the character of the light produced is an important consideration.

Efficiency of Lighting.

All artificial lighting consists in transforming a portion of the energy supplied into the radiant energy resident in that narrow band of the spectrum which produces the sensation of light in the eye. The only practical method conceived up to the present is to transform the energy of the fuel into heat by burning it in air, thereby by various means raising some appropriate body to incandescence; the body then emits radiation of all wave-lengths, of which a small fraction are so-called light-rays and the remainder are dissipated in heat. The process is crude and extravagant, and the amount of energy in a beam of light is only a small fraction of the heat in the fuel consumed to produce it.

The heat generated by a gas light has free avenues of escape, such as by admixture with the surrounding cold air, and in other ways. In an electric light the incandescent element is partly protected from loss of directly-convected heat by being enclosed in an hermetically-sealed bulb, which prevents the contact of cold air with the element. The efficiency of transformation to luminous radiation therefore is much higher than it is in the case of gas. The proportion is greatly reduced if we calculate the true efficiency from the fuel to the light-energy. With gas this efficiency is of the order of 1 per cent. With the most recent gas-filled tungsten lamp, about 8 per cent. of the energy of the current is converted into light. As this is only some 25 per cent. of the energy of the coal, the overall efficiency is of the order of 2 per cent. These figures are set out in Table III.

TABLE III.—LIGHT-EFFICIENCY OF LAMPS AND MANTLES.

Dissipation of energy in a 100-watt tungsten lamp and in an inverted gas light.

	Electricity.	Gas.
Heat loss by convection	25 per cent.	55 per cent.
,, ,, radiation	67 ,,	44 ,,
Light radiation	8 ,,	1 ,,
Energy in lighting agent . . .	100 ,,	100 ,,

Future Developments.

The potentialities of the production of light from electrical power are very wide. As the whole energy of the light produced by present methods is only about 2 per cent. of that in the fuel, it is possible that some new method may be devised which will make electric lighting much more efficient than is conceivably possible with gas. Some such methods are already in process of development. Every alteration or improvement in the method has its effect on the relative costs.

It is difficult to foresee the effect on the economics of the electrical industry of such a transformation if, and when, it occurs. This subject is, however, beyond the scope of this Paper.

Relative Cost of Lighting.

It is necessary to find a practical basis on which the efficiency can be determined. The true value of the efficiency is the ratio between the amount of energy in the visible radiation and that in the fuel consumed. It is difficult to determine either which portion of the band of radiation is to be regarded as "visible" and which "invisible," or the amount of energy in the whole visible band. The latter amount is not the essence of the problem, as the practical effect of the light in rendering objects visible is the main consideration; this effect is not necessarily proportional to the energy in the visible band. The efficiency must therefore be defined on an empirical and not on a scientific basis.

The practical value here adopted is the ratio of the amount of useful light, as measured by the photometer, to the amount of heat in the gas or electric current which is required to create it; that is, the number of spherical candlepower-hours generated per B.Th.U. expended, or inversely the number of B.Th.U. required to produce 1 spherical candlepower-hour. This conception is easier to understand than the more scientific "lumens per watt" basis, which the electrical industry have adopted as a measure of lighting efficiency.

The relation between these two units is

4π lumens = 1 spherical candlepower, which is a rate of light-expenditure.

1 watt = 3·416 B.Th.U. per hour, which is a rate of power-expenditure.

whence it follows that $x \dfrac{\text{lumens}}{\text{watt}}$ expresses the same efficiency as

$$y \frac{\text{B.Th.U.}}{\text{candlepower-hour}}$$

where $xy = 4\pi \times 3{\cdot}416 = 43$.

That is, $$y = \frac{43}{x}.$$

Thus, for instance, 9 lumens per watt $= \frac{43}{9} = 4{\cdot}77$ B.Th.U. per candlepower-hour.

This relation assumes that the spherical candlepower is a true measure of the total utility; that is, that all similar objects illuminated by a certain number of foot-candles are equally visible to all persons. That these assumptions are not accurate appears probable, and in this respect the present basis of comparison is unsatisfactory.

This question, however, is not material for the present discussion, for which it will be necessary to take the efficiency of lighting as the ratio of the candlepower-hours developed to the total B.Th.U., either in the form of gas or electricity, supplied.

Table IV.—Approximate Lighting-Efficiencies of New Lamps and Burners.

Source of light.	Equivalent lumens per watt.	Equivalent B.Th.U. per spherical candlepower-hour.
Vertical gas-mantles . . .	1·0	43
Ordinary inverted gas-burner . .	1·44 2·0	30 21·5
Gas, using regeneratively-heated air	2·15	20
Electric carbon-filament lamp .	3·0	14·3
High-pressure gas-burner . . .	4·3 5·0	10 8·6
Electric tantalum lamp	6·0 7·0	7·2 6·1
Electric tungsten vacuum lamp .	8·0 9·0 10·0	5·4 4·8 4·3
Electric tungsten gas-filled lamp .	11·0 12·0 13·0 14·0 15·0	3·9 3·6 3·3 3·1 2·9
Best modern electric lamp . .	16·0 17·0 18·0 19·0	2·7 2·5 2·4 2·25
Sodium lamp . .	20·0	2·15
Electric discharge lamp	30·0 to 40·0	1·44 1·07
Maximum hitherto attained experimentally .	70·0	0·62

Table IV gives the efficiencies thus calculated of various forms of light, arranged in order of increasing efficiency from the lowest to

the highest; the figures are set out to scale on the abscissa of Figs. 3, Plate 1, in two inverse ways.

Cost of Fuel.

The comparison of relative cost of the energy consumed (either as gas or as electric power) for the same amount of light can be made by the aid of Figs. 3, Plate 1. It is similar in general principle to *Figs. 1.* The equivalent prices of "heat" are in each case plotted together on the central ordinate so that each point represents the same cost of heat per 100,000 B.Th.U. The points on the abscissa represent B.Th.U. per spherical candlepower, or the equivalent in lumens per watt. They are so calculated that a diagonal line from a point on the abscissa to one on the central or price-ordinate will cut the second or cost-ordinate at such a point as will represent numerically the cost in pence of 10,000 spherical candlepower-hours; that is, of 125,000 lumen-hours. It is suggested that some such practical unit of light-quantity might be generally adopted, and assigned some such name as 1 "luxon," corresponding to 1 "therm."

One "luxon" would then represent the total amount of light delivered over a floor-space of x square feet at an intensity of y foot-candles during a period of z hours, where $xyz = 125{,}000$. It should be noted that a certain proportion of the light propagated is absorbed by the walls.

Alternatively, in order to ascertain the equivalent prices of gas and electricity for any two lighting-units whose efficiencies are known, diagonals may be drawn from the same point on the line of total cost to points on the abscissa representing the corresponding efficiencies reckoned in B.Th.U. per spherical candlepower-hour or in lumens per watt. The points where these cut the price-ordinate show the respective prices per unit at which the two sources of heat are equally economical.

Deterioration.

The practical question of the deterioration of the lamps and mantles is of importance. The life of an electric-light bulb is normally 1,000 hours, during which period it deteriorates by about 15 or 20 per cent. The rate of deterioration of a good gas-mantle is about one-third of this figure. The reduction of light is so gradual that it is usually not noticed until long after the mantle or bulb should have been discarded.

A suitable application of Figs. 3, Plate 1, would enable any problem relating to the economy secured by the use of different qualities of lamps or burners to be solved accurately.

The cost of fuel may be taken as equal when, for instance, the prices per unit using new inverted gas-mantles (30 B.Th.U. per candle-power-hour) and the best new tungsten lamps (16 lumens per watt) are respectively in the proportion of 10*d.* per therm and 3·85*d.* per unit. The graphical method of determining this is shown in Figs. 3, Plate 1, as an illustration. No valid practical comparison can be made unless the actual intensity of the lighting produced in each of the two cases is accurately measured by means of a photometer.

Total Cost.

Many considerations are comprised in the total cost, but most of these are not capable of rational calculation. The monetary values of the advantages and disadvantages of the two agents, as set out on p. 236, can only be estimated; they vary in different cases.

The ease with which an electric light can be switched on and off tends relatively to reduce the whole cost of that form of light by an amount which varies according to the use made of the room. The cost of time annually taken up in lighting gas-jets has an appreciable value, but it is impossible to estimate it. The possibility of regulation, although not often used, tends to reduce the annual cost of gas. These differences in use taken over a whole year might well amount to a substantial sum, which is wholly impossible to estimate.

There are other differences even less susceptible to calculation. Some persons find that electric lighting produces more trouble for their eyes than does gas lighting. There are some who affirm that they cannot use electric lighting at all because of the painful effect on their eyes. It may well be inquired whether such effects might not be obviated by the use of an appropriate shade or opalescent globe, or by some other similar device. Other persons believe that the heat and the products given off from a gas flame are advantageous, as they help to warm or to sterilize the room, or assist in the prevention of draughts. Such questions are individual to the user, and can hardly be considered in a general comparison.

A true comparison of the total cost in a room which has a white ceiling involves the additional cost of the more frequent cleaning of the ceilings which might be incurred by the proprietor when the dirtier of the two agencies was used, as a dirty ceiling absorbs and suppresses more light than does a white one. The soiling and loss of efficiency are progressive and are noticeably greater for gas than for electric light. It is often necessary either to incur the cost of cleaning the ceiling or to suffer the loss of efficiency or dissatisfaction caused by a dirty ceiling as compared with a relatively clean one.

Monetary values often depend on the idiosyncracies of the

individual concerned, and it is impossible to lay down figures in an absolute sense. The person concerned would have to decide how much per annum it would on the whole be worth to him to avoid these disadvantages. Whether or not definite conclusions on total relative costs can ever emerge on such matters is perhaps open to doubt.

Of a hundred different persons taken at random, a large proportion would decide in favour of electric lighting, on account of its convenience, whatever, within reason, the relative costs. Some would favour gas on account of its cheapness, but there are few who would claim that gas lighting for a house was generally superior in convenience to electric lighting.

The relative cost can only be measured by equipping the same house with both systems, each system giving an equal intensity of lighting, and observing the consumption in two successive periods, in which the two are used alternately. The Author has made this test on one house only, which was equipped with both systems to an approximately equal degree, as measured by a photometer, and he found that the equivalent costs of gas and electricity for general house-lighting obtained in this way are 10*d.* per therm and 3½*d.* per unit, using inverted gas-mantles and gas-filled electric lamps of about 30 and 3·5 B.Th.U. efficiency, respectively. The observations continued over an entire year in each case. This approximates to the value obtained from Figs. 3, Plate 1.

Street Lighting.

This appears to be on a different basis. Here the additional labour involved in lighting and in maintenance of the gas system is an important matter.

Here also there are numerous subsidiary considerations of a difficult character, for instance as to whether a given amount of light of one kind actually produces as much, or less, or more, useful effect for the pedestrian or the driver of a vehicle through the darkened streets as the nominally equivalent candlepower of the other kind, and as to whether one kind is or is not more penetrating in fog or mist than the other, as well as other similar considerations. It is the Author's experience that a good gas-lit system of street lighting produces a considerably better effect than an electric system.

Judged on the basis of candlepower only, apart from the labour involved, the relative cost of gas and electricity for street-lighting purposes is probably as follows. If electricity for street lighting by tantalum lamps (6 lumens per watt) is supplied at a price of ½*d.* per unit, the equivalent cost of compressed gas at 10 B.Th.U. per

TABLE V.—COSTS OF EQUIVALENT ILLUMINATION BY GAS AND ELECTRICITY.

GAS: Cost of 10,000 spherical candlepower-hours: pence.							ELECTRICITY: Cost of 125,000 lumen-hours: pence.								
Price per therm: pence.	Equivalent lumens per watt.						Price per		Lumens per watt.					
	0·86	1·07	1·43	2·15	2·85	4·3			6	8	10	12	15	20
	B.Th.U. per spherical candlepower-hour.						Unit: pence.	100,000 B.Th.U.: pence.	Equivalent B.Th.U. per spherical candlepower-hour.					
	50	40	30	20	15	10			7·2	5·4	4·3	3·6	2·86	2·15.
6	30	24	18	12	9	6	1·0	29·3	21·1	15·8	12·6	10·5	8·4	6·3
7	35	28	21	14	10·5	7	1·5	44·0	31·7	23·8	18·9	15·8	12·6	3·5
8	40	32	24	16	12	8	2·0	58·5	42·0	31·6	25·2	21·0	16·7	12·6
9	45	36	27	18	13·5	9	2·5	73·0	52·5	39·4	31·4	26·3	20·9	15·7
10	50	40	30	20	15	10	3·0	87·8	63·5	47·5	37·8	31·6	25·2	18·9
11	55	44	33	22	16·5	11	3·5	102·0	73·5	55·0	44·0	36·7	29·2	21·9
12	60	48	36	24	18	12	4·0	117·0	84·3	63·2	50·3	42·1	33·4	25·2

candlepower-hour, to compete on the same basis, and apart from questions of labour, would be about 10·5*d.* per therm.

Domestic Hot-Water Supply.

Requirements vary widely in different houses, according to the cleanliness maintained. The bulk of the demand is satisfied if hot water at a minimum temperature of 130° F. is instantly available in the necessary quantity at any hour between about 7 a.m. and 11.30 p.m. There are also certain requirements which may call for temperatures up to boiling point, which would not involve the general system. The heat necessary for certain purposes is shown in Table VI.

Table VI.—Usual Requirements per Person per Day.

Daily requirements.	Equivalents (100 per cent. efficiency).			
	B.Th.U.	Corresponding units of electricity.	Therms.	Cubic feet of gas (assuming C.V. = 500 B.Th.U. per cubic foot).
One very full hot bath	20,000	6·0	0·2	40
Usual hot bath . .	10,000	3·0	0·1	20
Four full hand-basins	2,000	0·6	0·02	4
General domestic requirements per person per day, excluding laundry and above requirements	5,000	1·5	0·05	10

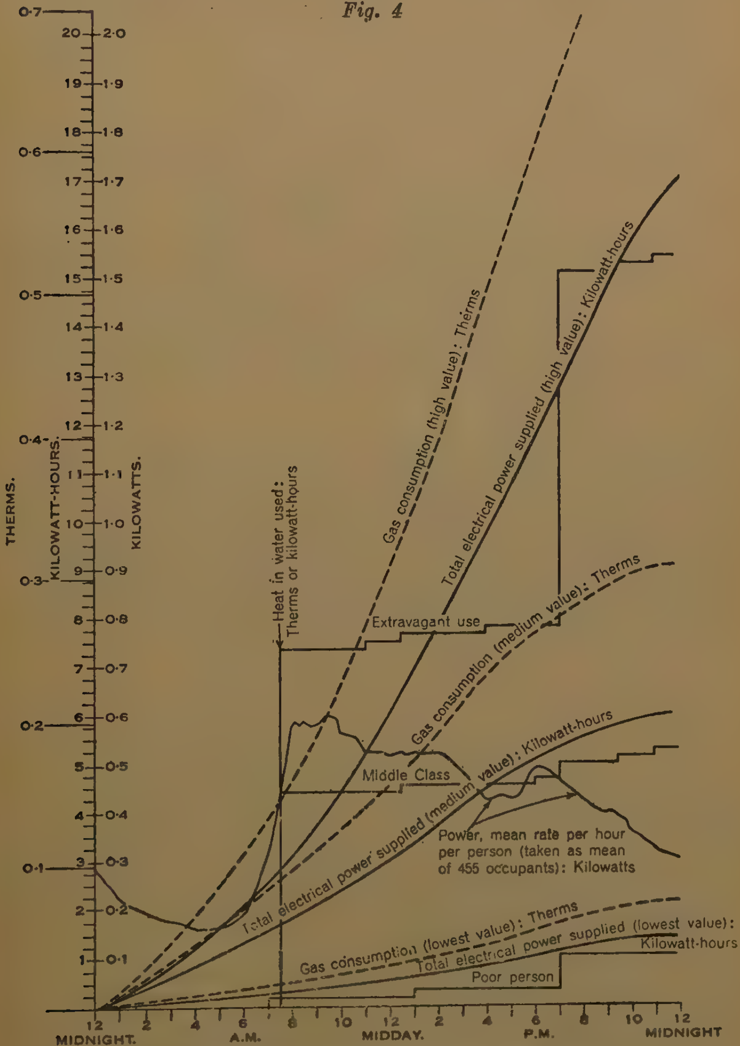
The amount of heat required daily for this service varies greatly according to the social standing of the individual concerned, as will be seen from Table VII, and according to whether the user has to pay in direct proportion to the amount used.

Table VII.—Maximum Total Heat Requirements per Person per Day for Hot-Water Supply.

	B.Th.U. per day.	Electric units per day.		Therms per day.	
		Efficiency 100 per cent.	Efficiency 90 per cent.	Efficiency 100 per cent.	Efficiency 50 per cent.
Poor person	3,000 to 10,000	0·9 to 3	1 to 3·5	0·1	0·2
Normal	30,000	9	10	0·3	0·6
High value	40,000	12	13	0·4	0·8
Extravagant . . .	50,000	15	16	0·5	1·0

The rate at which heat was actually supplied for hot water, as observed in houses of three grades at various times of day, and the actual consumption of power by the average user who had to

Fig. 4



DAILY CONSUMPTION OF HOT WATER PER PERSON.

pay for it, are shown in *Fig. 4*, which represents the mean results of observations in three different districts, taken over sixty different houses of various classes.

These results are lower than those calculated in Table VII; the totals depend largely on the number and size of baths taken.

It will be observed that the consumption of heat as hot water, and the use of the power for heating it, are far from simultaneous, owing to the heavy time-lag. An amount of water which has taken 5 hours to heat may be drawn off in 2 minutes.

Central, Local, or Instantaneous Supply.

In any case the demand may be met in one of three ways, either—

(1) By centrally-heating a storage-supply, which is always kept hot, and which is large enough to provide the required quantity immediately at any point.

(2) By gradual local heating by gas or electricity of a storage-supply appropriate to the immediate demand at each point likely to be required.

(3) By heating the water when required by instantaneous heaters of appropriate power.

Observations on these Methods.

(1) The first involves a centrally-placed boiler, a storage-cylinder, and a system of circulating pipes. The loss of heat incurred in keeping this circulation constantly hot is a considerable proportion of the total heat used, and depends on the efficiency of the insulation. When the heat is expensive this is an extravagant method. The equivalent prices by this method are in the proportion of gas at 10*d.* per therm to electricity at 0·55*d.* per unit.

(2) A "local" supply is much more economical.

(3) The instantaneous method calls for the consumption of a large amount of power or fuel in a short time. With electricity it is only rarely that such high power is available, and it is rarely used on this account. Thus if a basin containing ½ gallon of water at a temperature of 120° F. is to be drawn in 1 minute, the power required would be about 6 kilowatts. If a bath requiring 20,000 B.Th.U's. were to be drawn off in 3 minutes, 120 kilowatts would be necessary. Such powers are too expensive to supply in a private house for occasional service.

With gas, the corresponding rates of consumption would be respectively 50, and from 800 to 1,000, cubic feet per hour respectively. There is considerable danger inseparable from burning gas at so great a rate in a house, but a lower consumption increases the time of drawing off the hot water, which is often an intolerable nuisance. Although gas geysers are inexpensive their use involves considerable risk of accident. A local storage-supply, slowly heated, is to be preferred on the grounds of safety.

Differences between Gas and Electricity for Hot-Water Supply.

(1) Gas requires a separate furnace or boiler, but electrical heating can be applied in the interior of existing storage-cylinders.

(2) Gas, at usual prices, is about half the cost of electricity.

(3) Gas needs to be ignited, while electricity can be switched on from any point.

(4) Regulation and control by gas are easier and the heating may be much more rapid than can be effected by electricity, without incurring great expense.

(5) Electricity supplies the heat in a much cleaner manner at an efficiency of almost 100 per cent., which is unaffected by accumulations of fur. Gas gives off products of combustion and works at a much lower efficiency, which is reduced as fur collects on the heating-surfaces. Unless special provision is made for their evacuation, either by chimney or by some power-driven suction-device, the products will discharge into the air inside the house, causing sometimes smells and always an excess of humidity. Any metallic flue-pipe is subject to corrosion, and often to a down-draught.

(6) If a gas flame is extinguished or the combustion is incomplete, poisonous or explosive gases are distributed in the air inside the house.

(7) Gas apparatus requires more attention. Unless the apparatus is maintained in good condition, smells are produced and the efficiency falls seriously. Corresponding electrical apparatus requires no attention except for occasional cleaning and removal of scale.

Efficiency.

In this case the meaning of the term "efficiency" is clear; namely, the proportion of the heat in the energy used which appears in the hot water as drawn from the tap. Its value varies widely according to the amount of water drawn off from the storage-supply.

Let H denote the heat used (*a*) in heating the water, (*b*) per hour when the temperature is maintained.

" P " total heat stored in the system when fully heated from 55° F. to 130° F., including the water and the metal in the cylinders, heaters, pipes, and tanks.

" Q " total escape of heat from the system by convection and radiation (*a*) during the heating period, (*b*) when the system is maintained at full temperature for 1 hour.

Let R denote the total loss of heat in the products of combustion (*a*) during heating, (*b*) per hour.
,, S ,, total heat in the water drawn off from the storage-supply.
For gas, $H = P + Q + R + S$.
For electricity, $H = P + Q + S$, since $R = O$.

Efficiency from Cold (*Values* (*a*) *in above Definitions*).

For gas, $\frac{S}{H} = \frac{H - (P + Q + R)}{H} = 1 - \frac{P + Q + R}{H}$.

For electricity, $\frac{S}{H} = \frac{H - (P + Q)}{H} = 1 - \frac{P + Q}{H}$.

Steady-State Efficiency (*Values* (*b*) *in above Definitions*).

For gas, $\frac{S}{H} = \frac{H - (Q + R)}{H} = 1 - \frac{Q + R}{H}$.

For electricity, $\frac{S}{H} = \frac{H - Q}{H} = 1 - \frac{Q}{H}$.

The value of Q is much greater for a central system than for a local one, and depends on the perfection of the insulation. Its value in an uncoated system is often as high as $0{\cdot}9H$, but in a well-coated system with a large use of hot water it is sometimes not greater than $0{\cdot}25H$. The net efficiency of a local heater depends on the values of S and Q; it can be calculated for various assumed values of S from the values of Q, in Table VIII, which are claimed by well-known makers of plants of this type.

Loss by Heat-Leakage.

With water maintained at a constant temperature of, for example, 160° F., the daily insulation-loss from a small local storage-heater of the best construction is uniform and has values of the order given in Table VIII.

TABLE VIII.—LOSS OF HEAT THROUGH INSULATION.

Capacity: gallons.	Electrically Heated.		Gas Heated.	
	Heat loss by leakage: B.Th.U. per 24 hours.	Power wasted by heat-leakage: units per day.	Heat loss by leakage: B.Th.U. per day.	Gas wasted by heat leakage: therms per day.
2	2,500	0·73	7,000	0·07
5	3,500	1·03	8,000	0·08
12	5,000	1·46	10,000	0·10
18	7,500	2·20	13,000	0·13
24	8,500	2·50	16,000	0·16

The usual daily efficiency of a good local heater is about 90 per cent. in the case of electrical heating, and 50 per cent. where gas heating is used, but varies according to the amount of hot water used.

A local gas heater loses about double the amount of heat that an electrical heater does, because it cannot be so perfectly insulated. The passage through which the products of combustion escape also permits leakage of heat from the water when the gas is extinguished. The small gas flame required to maintain the temperature when no water is being drawn off, and to ignite the main flame, operates at a low efficiency, whereas that of the electrical element is always 100 per cent. A flame smaller than one burning about 1 cubic foot per hour is easily extinguished. The hourly gas-consumption for these small storages is such that a gas-heated supply is tolerable where the products of combustion are allowed to escape into the air of the house, although this is not a desirable arrangement.

Daily Efficiency of Local Heaters.

This expression is used to signify the ratio between the amount of heat in the water drawn off daily and that in the fuel supplied. Its value varies greatly (according to the daily amount of hot water used) from zero, if no water is drawn, up to the full value when the heater is in continuous use up to its maximum power.

A rough estimate of the degree of variation may be obtained from the following rough analysis, using the same notation as defined on p. 247, and in addition indicating the total number of gallons drawn off per day as G. The temperature is assumed to be maintained at 130° with an inlet temperature of 55° F. Then $S = 10G \times 75$, or $S = 750G$, since a gallon of water weighs 10 pounds.

Assuming that the particulars given in Table VIII apply to this example, and comparing an 18-gallon-capacity electric heater with a gas heater of the same size, it will be seen that the energy lost daily by the leakage of heat is :

For an electrical heater, 2·2 units, representing .	7,500 B.Th.U.
For a gas heater, 0·13 therms, representing . .	13,000 B.Th.U.

Assuming that the gases escape at about 400° F., and that there is 200 per cent. excess air, R may be taken as $0{\cdot}35H$, which is probably an approximate average for most heaters.

The efficiency of a gas heater then becomes

$$\frac{S}{H} = \frac{750G \times 0{\cdot}65}{Q(b) + 750G}$$

and for an electrical heater, the efficiency will be

$$\frac{S}{H} = \frac{750G}{Q(b) + 750G}.$$

Applying these rough expressions to four different daily consumptions from an 18-gallon heater, the figures given in Table IX are obtained for the daily efficiencies in the two methods of heating.

TABLE IX.—COMPARISON OF THE EFFICIENCY OF AN 18-GALLON HEATER WITH EITHER GAS OR ELECTRIC HEATING.

Daily consumption: gallons	20	50	100	200
Efficiency with gas heating: per cent.	35	48	56	60
Efficiency with electric heating: per cent.	69	84	92	95
Equivalent [1] price of electricity, assuming gas costs 10*d.* per therm: pence per unit	0·675	0·60	0·56	0·54

[1] See *Fig. 1.*

Experience shows that, in general service, an approximate equivalent price to gas at 10*d.* per therm is electricity at 0·7*d.* per unit, due to the reduction in the efficiency of the gas burner when working at low powers. The cost per person of a daily supply of 20,000 B.Th.U. is set out in Table X.

TABLE X.—LOCAL DOMESTIC WATER HEATING.

Cost of a Daily Supply of 20,000 B.Th.U. per Person.

Gas Heated.				Electrically Heated.						
Price of gas per therm: pence.	Daily efficiency: per cent. 50	60	70	Price of electricity per unit: pence.	Equivalent price per 100,000 B.Th.U.:* pence.	Daily efficiency: per cent. 60	70	80	90	100
	Cost per person per day: pence.					Cost per person per day: pence.				
6	2·4	2·00	1·71	0·5	14·6	4·86	4·16	3·64	3·24	2·92
7	2·8	2·33	2·00	0·75	22·0	7·3	6·24	5·46	4·86	4·38
8	3·2	2·66	2·28	1·0	29·3	9·8	8·32	7·28	6·50	5·84
9	3·6	3·00	2·56	1·5	44·0	14·6	12·5	13·1	9·73	8·76
10	4·0	3·33	2·86	2·0	58·5	19·5	16·7	14·6	13·0	11·7
11	4·4	3·66	3·14	2·5	73·0	24·4	20·8	18·2	16·2	14·6
12	4·8	4·00	3·42	3·0	87·8	29·3	25·0	21·8	19·5	17·5

* Equivalent to 1 therm of gas.

Space-Heating of Buildings.

A comparison between all fuels used for this purpose has been made elsewhere[1] in some detail by the Author. A proper comparison between gas and electricity involves difficult questions relating to the functions of convected and radiant heat, as well as matters of ventilation and "effective temperature," which will not be considered here.

Efficiency.

It is difficult to formulate a satisfactory definition of the word "efficiency" as applied to space-heating. Its apparent meaning, namely, the proportion of the heat in the fuel actually delivered in some form or other into the room-space, would, if applied indiscriminately, give a wholly incorrect impression of the real efficiency of the heating-apparatus as a means for producing comfortable conditions. This is because the same amount of heat delivered to the same room in different ways produces different results in comfort, according to the way in which it is distributed. Nevertheless, this is the only practicable general definition, owing to the complexity of the conditions affecting the rate of heat-loss. To make a satisfactory comparison, the assumption must be made that the heat is distributed in the two cases by the same general method; that is, with a similar distribution and sub-division between radiant and convected heat, and with similar thermal effects. Identity of effect is, however, neither easy to produce nor to measure. Conditions can be produced by electricity, such as those resulting from ceiling panel-heating, which cannot be produced by gas, so that the comparison is in any case somewhat academic. No valid comparison would be possible between, for instance, heating by means of a gas fire, and by means of electrical ceiling-panels, because the thermal effects produced would be entirely different and could not be measured at all by means of thermometers or other simple apparatus.

Central and Local Heating.

A building can be warmed in two ways, namely:

(1) By central heating.

(2) By local heating.

By "central heating" is meant the method of heating water in a

[1] "The Relative Fuel Economy of Electricity, Gas, Oil, and Solid Fuel as Heating Agents," Journal Inst.E.E., vol. 72 (1933), p. 269.

central boiler and circulating it to radiators. By "local heating" is meant any method in which the heat is generated in the room where the heat is required.

When the same method of dissipating the heat is employed, the former type of plant inevitably uses more heat than the latter. It is necessary to make a separate comparison between gas and electricity in each of the two systems in order to obtain a fair estimate of their respective advantages.

(1) *Central Heating.*—An electrical boiler, for reasons of economy, must have a large capacity, the water in it being heated by electrical power, during non-peak periods, when the power can be supplied cheaply. The boiler must be able to store enough heat to satisfy the requirements of the building during the hours when the electrical power can only be supplied at higher rates. A gas-fired boiler, on the other hand, can be supplied with gas at any hour, since a large reserve of gas is contained in the holders at the gasworks, and the time at which it is used is more or less immaterial to the gas-company. There is therefore no necessity to heat a large storage tank.

It will be assumed in the following comparison that, apart from the boiler the remainder of the system is the same for either of the two methods of heating, although this would not be the case in practice.

The direct cost of an electrically-heated boiler will, in all cases, very greatly exceed that of a gas-fired boiler, and the cost of the former is further increased on account of the large excavation and expensive building-work required to accommodate the large cylinders in the basement, but the primary efficiency of the conversion of electrical energy into heat in the water stored in the container, is substantially 100 per cent., the figure for a gas-fired boiler being 80 per cent.; these figures will, however, be considerably reduced owing to the inevitable heat-leakage. The actual value for the whole boiler-installation, taken from the fuel to the water, may be taken as 85 per cent. for electricity and 70 per cent. for gas, for continuous heating over 24 hours. The figures are very variable when the heating is discontinuous.

The reasons for this are fully dealt with in the previous paper [1] by the Author. Referring to *Fig. 1*, the fuel costs of the two sources of heat are about equal with gas at 10*d*. per therm and electric power at 0·4*d*. per unit. To obtain the total costs, capital charges would have to be added to these figures, and some allowance would have to be made for the different costs of labour. It is probable that, taking these items into account, in an average case the

[1] *Ibid.*

equivalent values of gas and electricity would be about 10*d.* per therm and 0·2*d.* per unit.

Relative Advantages.—The advantages of electrical equipment lie in greater convenience and cleanliness. The storage method has the additional advantage that a large reserve of heat in the storage-tanks makes the heating-up of the radiator-system much more rapid than is possible with the gradual heating of the water by gas. A gas-boiler must be provided with an adequate chimney and requires more labour and maintenance. A comparison of the relative degree of danger between the two is difficult. The electrical installation might cause the immediate death of any person touching a piece of live metal, while mishandling of the gas-plant or serious leakage might cause gas-poisoning or a disastrous explosion.

An electrical installation is more liable to breakdown than a plant heated with gas, but if the breakdown is, as usual, of short duration, it entails little or no inconvenience. A prolonged breakdown of an electrical system might enforce a temporary vacation of the building, whereas a similar breakdown with gas equipment could be remedied temporarily.

(2) *Local Heating.*—The warming of buildings by local heating involves completely different considerations. For various reasons the consumption of energy for local heating is much less than for central heating, the former method usually requiring about half the heat-units necessary with the latter.

There are two general methods in practical use by which either source of heat can be used locally :—

(*a*) The incandescent fire.
(*b*) Low-temperature surface-heating.

(*a*) *Incandescent Fires.*—The differences between a gas fire and an incandescent electric heater make a correct comparison between them difficult. The former is used in conjunction with some form of chimney or flue ; this is usually 9 inches by 9 inches in cross section (such as is used for a coal fire), giving rise to a large loss of heat up the chimney, but at the same time having a valuable ventilating effect. The flue may, however, be one of the small "Nautilus" flues, having a size of 10 inches by 2 inches, formed as hollow concrete slabs built into the wall, with which the loss of heat is much less and the ventilating effect is negligible.

An electric fire, on the other hand, is independent of a chimney, is sometimes portable and can be placed in any position in a room where the heat emitted from it is localized and used to full advantage ; the efficiency is then clearly 100 per cent. The room can thereby be made habitable without fully heating the whole space. This

difference is essentially due to the generation of products of combustion by a gas fire.

Distribution of Heat.—The heat from a gas fire is necessarily at a high temperature, and is distributed from one position in a room, generally from one side only. The result is that the effective temperature varies widely between different points in the room. It may be much too hot for comfort near the fire, and much too cold far away from it. Electrical heating-plants may, however, be subdivided into suitable units, each at any desired temperature, without trouble or loss, the units being placed at as many points and in such positions as may be necessary to produce a uniform effective temperature over the whole area.

If, for convenience, an electric fire is placed in an existing fireplace the flue may be blocked to prevent some of the clean but expensive electrically-derived heat from being carried away to the outside air. This is a considerable hygienic disadvantage and makes heating by this means, although much more efficient technically, definitely less pleasant than by means of a corresponding gas fire with a large flue, which causes the air in the room to be changed from five to ten times per hour. In any satisfactory comparison, allowance must be made for this difference.

The heat emitted by an electric fire is propagated both as radiation and as convection, but the proportion between them varies with the design of the fire. It is usually about 65 per cent. radiation and 35 per cent. convection. The primary radiant efficiency of a modern gas fire is usually from 40 to 45 per cent., but in some forms the proportion rises as high as 60 per cent. In general, however, well below 50 per cent. of the heat generated is propagated by radiation.

In addition to radiant heat, a gas fire emits into the room a certain amount of convected heat, generally from 5 to 10 per cent. of the total, which is sometimes mixed with a small proportion of the products of combustion which escape from the throat of the chimney. This is the reason why it is sometimes found that a gas fire has a somnolent effect on the occupants of the room. With a fire that is well designed and fitted there is no such effect, unless the power of the fire is too great for the room. If the combustion is effected completely the products which escape into the room do no harm except that they increase the humidity and probably cause the surface corrosion of metal fittings in the room. The over-all efficiency of a gas fire, including both radiant and convective heat, is usually from 45 to 50 per cent., the remainder of the heat being lost in the flue gases; a strong ventilating action is thus obtained, which draws from the room much of the air which has been indirectly warmed by

the radiation. This complication is considered below. There are thus two ways in which the two sources of heat can be compared:

(i) A comparison of the cost of the heat delivered into the room, as radiation only, by gas and electricity.

(ii) A comparison between the cost after allowing for the effect of the strong ventilating action induced by the gas fire.

The first of these can be computed by the use of *Fig. 1*; it has little application to practical conditions.

Table XIV, p. 258, is derived from this, giving the relative costs in pence of 100,000 B.Th.U. of radiant heat only.

Ventilation.—The hygienic condition of a room is greatly improved by adequate ventilation. The cost is not only that of the waste gas which serves to maintain it, but also that of the heat, propagated as radiation, in the warm air of the room, and subsequently removed by the chimney.

A gas fire will often cause the air in the room to be completely changed five, or even more, times per hour, depending on the arrangement of the chimney-throat, thus discharging up the chimney the amount of heat needed to warm this volume of air from the external to the internal temperature of the room. The effect of this is to increase the amount of gas that it is necessary to burn in order to maintain the temperature of the room at the required level.

If this heat is assumed to be lost, the nominal efficiency of the fire is materially decreased. Thus, if a certain room, having a capacity of 2,000 cubic feet, normally requires 6,000 B.Th.U. per hour to warm it to 65° F. with two interchanges of air per hour, a fire of 50 per cent. efficiency, and using 25 cubic feet of gas per hour, would be necessary. If the waste heat from this fire procures an additional, and possibly unnecessary, ventilating effect of, for example, 10,000 cubic feet per hour, this alone would add about another 6,000 B.Th.U. to the heat required to maintain the room at 65° F. A gas fire using 50 cubic feet of gas per hour would therefore be necessary. Thus, if the comparison is based on the original requirements, the efficiency of the fire, from that point of view, would be 25 per cent. instead of 50 per cent., if compared with an electric fire of 100 per cent. efficiency which only procures the desired two interchanges of air. A direct comparison between the efficiencies of the two fires involves, therefore, some convention in regard to the loss of heat through the excessive ventilation that is induced by a gas fire.

A similar ventilating effect could be secured by the aid of electricity only, by the installation of a small electric fan drawing air from the room and discharging into the chimney or through some opening,

through which the warmed air in the room could be evacuated to the outside of the building. Such provision is, however, rare in a private house or office. It is assumed to be provided in the following comparisons, in order to equalize the effects of the two sources of heat. The consumption of electric power for driving the fan will usually be about 5 per cent. of the power used to generate heat. This matter is of such importance as to call for a simple analysis.

Let H denote the heat in the gas burnt in 1 hour.
,, E ,, radiant efficiency.
,, F ,, convective efficiency.
,, R ,, proportion of the heat lost in the flue-gases.
,, Q ,, heat required in the room for exposure only per degree (not considering ventilation).
,, N ,, number of interchanges of air per hour.
,, V ,, volume of room.
,, T ,, temperature rise required.

Let the specific heat of the air be taken as 0·243 and the weight per cubic foot as 0·0761 pounds.

Then the operating efficiency

$$= \frac{H(E + F) - 0{\cdot}243 \times 0{\cdot}0761\ N.V.T.}{H}.$$

Also, $$E + F + R = 1.$$

or $$HR = H(1 - E - F).$$

Again, $H(E + F) = T(Q + 0{\cdot}018\ N.V.).$

That is, $$H = \frac{T(Q + 0{\cdot}018\ N.V.)}{E + F}.$$

Regarding ventilation as wasted heat, the operating efficiency is

$$\frac{QT}{H} = \frac{H(E + F) - 0{\cdot}018\ N.V.T.}{H}$$

In Table XI, the following values are assumed: $T = 35°$ F.; $(E + F) = 50$ per cent.; $Q = \frac{V}{20}$ or $V = 20Q$. These values apply to an average case.

TABLE XI.—COMPARISON OF OPERATING EFFICIENCY WITH NUMBER OF INTERCHANGES OF AIR IN ROOM, USING A GAS FIRE.

Inter-changes of air in room per hour: N.			Total heat required per hour: H.	Operating efficiency: per cent.
0	$H = \frac{QT}{E+F} = \frac{35Q}{0 \cdot 5}$	=	$70Q$	—
	Operating efficiency $= \frac{35Q}{70Q}$	=	—	50
2	$H = \frac{35Q + 0 \cdot 018 \times 2 \times 20Q \times 35}{0 \cdot 5}$			
	$= \frac{35Q + 25Q}{0 \cdot 5}$	=	$120Q$	—
	Operating efficiency $= \frac{35Q}{120Q}$	=	—	29
5	H	=	$196Q$	—
	Operating efficiency $= \frac{35Q}{126Q}$	=	—	18
10	H	=	$322Q$	—
	Operating efficiency $= \frac{35Q}{322Q}$	=	—	11

Making the same assumptions and calculations for an electric fire, and assuming the electrical power required for a fan to be 5 per cent. of that required for heating (which reduces the primary efficiency of the stove itself to 95 per cent.), the figures given in Table XII are obtained.

TABLE XII.—COMPARISON OF OPERATING EFFICIENCY WITH NUMBER OF INTERCHANGES OF AIR IN ROOM, USING AN ELECTRIC FIRE.

Inter-changes of air in room per hour: N			Total heat required per hour: H.	Operating efficiency: per cent.
0	H	=	$35Q$	—
	Operating efficiency $= \frac{35Q}{35Q}$	=	—	100
2	$H = \frac{35Q + 25Q}{0 \cdot 95} = \frac{60Q}{0 \cdot 25}$	=	$63Q$	—
	Operating efficiency $= \frac{35Q}{63Q}$	=	—	55·5
5	H	=	$103Q$	—
	Operating efficiency $= \frac{35Q}{103Q}$	=	—	34·0
10	H	=	$170Q$	—
	Operating efficiency $= \frac{35Q}{170Q}$	=	—	20·5

The operating efficiencies for gas and electricity for the same number of interchanges of air per hour are therefore as shown in Table XIII.

TABLE XIII.

Number of interchanges of air per hour . . .	0	2	5	10
Operating efficiency with gas fire : per cent . .	50	29	18	11
Operating efficiency with electric fire : per cent.	100	55·5	34	20·5

This analysis does not take into account the economic effect of the ease of control of the electric fire, nor the great advantage that a gas fire can be turned low. It is impossible to estimate the relative values of these two features, and they are therefore assumed to be of equal value. Tables XIV and XV give comparative costs of gas and electric fires with and without ventilation losses.

TABLE XIV.—RELATIVE COSTS OF GAS AND ELECTRIC INCANDESCENT FIRES. COST OF RADIANT HEAT ONLY WITHOUT VENTILATION.

Gas Fire.					Electric Fire.					
Price per therm : pence.	Radiant efficiency of fire.				Price per unit : pence.	Radiant efficiency of fire.				
	35	40	50	60		50	55	60	65	100
	Cost of 100,000 B.Th.U. delivered as radiation only : pence.					Cost of 100,000 B.Th.U. delivered as radiation only : pence.				
5	14·3	12·4	10	8·3	0·4	23·5	21·5	19·6	18·0	11·7
6	17·2	15·0	12	10·0	0·5	29·5	26·8	24·5	22·5	14·7
7	20·0	17·4	14	11·6	0·6	35·2	32·0	29·5	25·0	17·6
8	23·0	20·0	16	13·3	0·7	41·0	37·5	34·1	31·5	20·5
9	25·8	22·5	18	15·0	0·8	46·8	43·0	39·1	36·0	23·5
10	28·5	25·0	20	16·6	0·9	52·7	48·0	44·1	40·5	26·5
11	31·5	27·5	22	18·4	1·0	58·6	53·5	49·1	45·0	29·3
12	34·4	30·0	24	20·0	2·0	117·0	107·0	98·0	90·0	58·5

Equivalent prices for radiation only are 10*d.* per therm for gas and 0·5*d.* per unit for electricity. The probable practical equivalents are 10*d.* gas and 1*d.* for electricity.

Table XV.—Total Net Costs per 100,000 B.Th.U. for Gas and Electric Fires, including Equivalent Ventilation Effects.

Gas.					Electricity.				
Price of gas per therm: pence.	Interchanges per hour.				Price per unit: pence.	Interchanges per hour.			
	10	5	2	0		10	5	2	0
	Operating efficiency including ventilation: per cent.					Operating efficiency of electric heater and ventilator: per cent.			
	10	20	30	50		20	35	55	100
	Cost of 100,000 useful B.Th.U.: pence.					Cost of 100,000 useful B.Th.U.: pence.			
5	50	25	16·5	10	0·5	73	42	26·5	14·6
6	60	30	20	12	0·6	88	50	32	17·6
7	70	35	23	14	0·7	102	59	37	20·5
8	80	40	26·5	16	0·8	116	67	42·5	23·5
9	90	45	30	18	0·9	130	75	47·5	26·5
10	100	50	33	20	1·0	146	84	53	29·5
11	110	55	36·5	22	2·0	293	168	106	59
12	120	60	40	24	3·0	438	252	159	88

Note.—It is assumed that provision for electrically-operated ventilation is supplied, equal to that produced by the gas fire required.

Theoretical equivalent prices, including ventilation effects, are gas at 10*d.* per therm and electricity at 0·6*d.* per unit; that is, gas at x pence per therm is equivalent to electricity at $\frac{x}{16}$ pence per unit. The equivalent figures have been determined experimentally as x pence per therm and $\frac{x}{10}$ pence per unit.

The significance of these results will be appreciated if reference is made to Table XVI, which shows these calculations applied to a room in which experiments have been made by the Author. The room was maintained in each case at the same temperature with a varying number of interchanges of the air per hour.

TABLE XVI.

Number of interchanges of air per hour.	Gas Fire.		Electric Fire.		Equivalent price per unit, taking gas as 10*d*. per therm: pence.
	Heat-units supplied per hour: B.Th.U.	Volume of gas burnt per hour: cubic feet.	Heat-units supplied per hour: B.Th.U.	Power consumed per hour: units.	
0	7,000	14	3,500	1·02	0·69
2	12,000	24	6,300	1·84	0·65
5	19,600	39	10,300	3·00	0·65
10	32,300	64	17,000	5·00	0·65

It will be noted from the above results that, although liberal ventilation, as automatically provided by a gas fire, is no doubt valuable, it is very expensive. In the above case the consumption when the ventilation in cold weather was normal, namely, two interchanges per hour, was 24 cubic feet or 2 units, while with ten interchanges the hourly increase required on these figures was 50 cubic feet of gas or 3 units of electricity.

It should also be noted that the combustion of gas as a means expressly for procuring ventilation (apart from the production of heat), is about ten times as expensive as the electric current required to drive a fan for the same purpose.

(*b*) *Surface Heating.*—The other general method of local heating is to maintain the temperature of a hot non-incandescent surface in the room, which functions in the same manner as ordinary radiators, hot panels or pipes. This subject has been fully treated elsewhere [1] by the Author. A brief summary only is possible in this Paper.

In former methods of using gas for this purpose the products of combustion were allowed to escape into the surrounding air. In this way the full 100 per cent. of the heat in the gas is apparently delivered into the room, but the general public object to this method of using gas, on the grounds that:—

(i) The gas is not always completely burnt and therefore gives off odourous products of combustion.

(ii) The air of the room is too much humidified by the combustion of the hydrogen in the fuel.

(iii) Gas is rarely free of all traces of sulphur, the combustion of which produces corrosive gaseous oxides of sulphur.

(iv) It produces an undesirable effect on the air of the room.

As these are regarded as grave disadvantages gas is not now

[1] Comm. No. 70, Proceedings Inst. Gas Engineers, Vol. 82 (1933).

generally used in this way. It is only so used where cheapness is the sole consideration. The only other way in which gas can be generally employed is by extracting the products of combustion direct from the outlet of the heater by means of a chimney, or else by means of a power-driven fan or other power-driven appliance placed in some convenient position outside the room and withdrawing the products through an appropriate system of copper tubes. This device has been successfully employed in experimental installations, although it is not yet in wide use.

The surfaces may, however, be heated electrically, and this method is very convenient, as it only calls for the provision of the necessary cables to carry the power to the elements of the heating surface, which is generally in the form either of tubes, panels, or ordinary radiators.

The use of gas, with the extraction device alluded to, is more troublesome and expensive to install, although when installed it is much cheaper to operate. The only portion of the gross heat of the gas not delivered into the room is that removed by the products, and as these are generally at a temperature below 200° F., at which temperature they carry away some 10 or 15 per cent. of the gross heat of the gas, the efficiency of this method of using gas is from 85 to 90 per cent. against the 100 per cent. which can be allowed for when using electrical power. Thus the relative operating costs are, by calculation, gas at 10*d*. per therm and electricity at 0·4*d*. per unit.

To the costs for gas heating must be added the cost of running a fan, which, however, only requires about 60 watts. Taking this and other small costs into account, it is probable that a more correct proportion would be gas at 10*d*. per therm and electricity at 0·5*d*. per unit.

Cooking.

The power used in cooking probably represents one of the largest fields in domestic economy for the employment either of gas or electricity. The comparison has been fully dealt with by the Author elsewhere.[1] A brief summary only can be given here.

Relative Advantages and Disadvantages.

Electricity is cleaner in use and the apparatus generally is, in consequence, of smarter appearance. A gas cooker is much more rapid in action than an electric cooker, since the maximum power

[1] Lecture on "Tests of Comparative Costs of Fuels for Domestic Purposes." Joint Gas Conference at Birmingham. Published by British Commercial Gas Association.

of a gas burner can be concentrated on the cooking vessels immediately the burner is ignited. Gas provides much better facilities for rapid heating, as the supply can be made much greater; the cost of electrical cables of adequate size for large powers would be prohibitive. With an electric heater there is greater absorption of heat by the surroundings, and as domestic cooking operations are generally conducted from cold, this feature reacts materially on the time occupied, which with electric power is 70 per cent. greater than with gas. An electric cooker is more comfortable to use than a gas cooker because of the hot products of combustion of the latter.

Danger.

The possibility of danger is probably equal. The danger from gas lies in its poisonous and explosive character, but in practice accidental damage in consequence of these properties is rare. The possibility of shocks due to defective insulation of an electric cooker is about equally negligible in a properly-made plant. A gas cooker is much easier for a cook to understand than an electric, as the amount of heat being generated is immediately visible and can be easily controlled from very low value to the maximum value. The corresponding electric heater has, at most, two or three steps, and the indications on the switch have to be read by the cook. In addition, special cooking-vessels with machined flat bottoms have to be used with electrical cookers. In a prolonged series of trials carried out by the Author in the same household and with the same persons, the amount of heat used in a gas cooker was from 50 to 100 per cent. greater than in an electric cooker, but for isolated meals the excess was much less, from 15 to 40 per cent. per the average value.

The wastage of weight in the food cooked in an electric cooker is less than in a gas oven, on account of the removal of the vapours by the products of combustion in the latter case. The relative cost of gas and electricity, taken over a long period, was found to be that electricity at 0·5*d*. per unit is the equivalent of gas at 10*d*. per therm.

Since these experiments were made the efficiency of electric cookers has been materially improved. By calculation, it is estimated that, if the same experiments had been made with the most recent type of electrical cooker, the results would have been that gas at 10*d*. per therm was the equivalent of electricity at about 0·7*d*. per unit.

Furnaces.

The general comparison between gas and electricity as sources of heat for furnace-work is extremely difficult, on account of the wide

range of designs and the great variety of appliances to which the general term " furnace " may be applied.

The fundamental difference between the two sources of heat is that a considerable fraction of the total heat used in a gas furnace must, of necessity, be lost in the products, which cannot be evacuated at a low temperature. A further difference lies in the fact that a great variation in the value of the efficiency of a gas furnace may be caused by an alteration in the conditions of combustion; that is, in the amount of excess air.

There are no such problems with an electric furnace. In this case, of the total heat used, the only fraction lost is that arising from conduction through the furnace walls, from accidental losses due to constructional defects, and from the operation of the furnace when inserting or removing the substance which is to be heated.

The outside of an electric furnace is cooler than that of a gas-fired furnace, and in some respects the former is more convenient to operate. The interior temperature of a gas furnace varies from point to point much more than that of an electric furnace, the temperature being highest in the immediate neighbourhood of the flame or where the flame actually impinges on the work; a controlled variation of temperature is, however, sometimes a desirable feature.

There need be no variation in the temperature inside an electric furnace, but if such a variation is desired, it is less easy to secure than with gas firing. A gas furnace has the advantage that the heat can be made either of a reducing or of an oxidizing character, and can be accurately controlled as required by the regulation of the conditions of combustion. If an oxidizing flame is required more air is admitted with the gas, and if a flame of a reducing character is required, less air than normal is supplied.

Similar results can only be obtained with an electric furnace by introducing gases into the furnace; this, however, causes complications and a corresponding increase in the loss of heat, on account of the convection caused by the evacuation of the gases.

Efficiency.

Great variations in the true efficiency are possible, according to the amount of work done in the furnace at one time. It is, therefore, practically impossible to obtain figures which would be generally applicable either for absolute or for comparative efficiencies. A rough analysis of the meaning of the term can be made on the lines suggested on p. 228.

The products escaping from the furnace proper must be at a high temperature, at or near that of the furnace itself. The losses and the

limit of efficiency possible for a primary furnace with perfect insulation, but without regeneration, can be determined from *Fig. 2*. The degree to which losses in the flue gases occur, and the alteration in this figure with variation of excess air, will be plain from an inspection of *Fig. 1*.

Thus, assuming the temperature of the furnace is maintained at 1,250° F., this would be the temperature at which the primary flue-gases will escape. Even if the furnace-walls were perfectly insulated so that no losses took place through them, the flue-gases would carry away, with no excess air, about 38 per cent., and with 100 per cent. excess about 58 per cent., of the total heat in the gas, leaving the maximum conceivable efficiency 62 per cent. and 42 per cent. respectively, without any allowance for the escape of heat by conduction.

Regeneration.

It is possible to conserve a considerable portion of the heat which would otherwise escape from a gas furnace by using some of it for pre-heating the air and gas and the residual for heating the material before it is introduced into the furnace; this arrangement considerably reduces the amount of heat discharged to waste, but at the same time it necessarily increases the amount lost by conduction. By such means overall efficiencies up to about 40 per cent. can be attained. These factors, however, depend greatly on the design of the furnace.

It is probable that the relative efficiency of the two heating agents can only be determined by empirical comparisons between different furnaces specially designed for the same duty; in all cases the amount of heat necessary from gas is greatly in excess of that required from electrical power, the former figure being generally about 80 per cent. or more in excess of the latter.

Thus, for example, the heat needed to raise the temperature of 1 ton of steel to about 1,650° F. would be about 1,800,000 B.Th.U., or 18 therms, of coal gas and only about 1,000,000 B.Th.U., or about 295 units, of electrical power, the former being, therefore, 80 per cent. in excess of the latter. The general consensus of opinion of those who have used furnaces of both types is that, with gas, the heat required is from 80 to 100 per cent. in excess of that required when electricity is used. Exact experimental information on this subject is very difficult to obtain.

The actual efficiency of an ordinary regenerative gas furnace, when economically loaded, is generally of the order of from 30 to 40 per cent., that of an electric furnace being from 55 to 60 per cent.

It is probably safe to take these figures as representative for most cases, which gives the efficiency of gas as from 55 to 65 per cent. compared with electricity taken at 100 per cent.

Welding and Cutting.

The difficulty of determining the value of the efficiency in welding is so great that it may perhaps be said that the term cannot properly be applied to this process. The only method by which a comparison can be made is to determine the amount of heat required to deposit a given quantity of metal, such as, for example, 1 pound.

With gas this amount would be about 16,000 B.Th.U. or 32 cubic feet, and when the same operation is carried out by electrical power the total amount required would be about 4,200 B.Th.U., so that about four times as much heat is required for this purpose from gas as from electrical power. These figures probably give an approximate idea of the comparison between the two agents for welding and similar purposes. They may be reduced to nominal efficiencies by assuming the value for electrical power as 100 per cent., according to which the efficiency of the gas process would be roughly 27 per cent. This figure is probably a fair general approximation, and equivalent prices can then be determined by reference to *Fig. 1*.

Thus, if gas is supplied for industrial purposes at 4*d*. per therm, the corresponding price of electrical power to perform the same work at the same cost would be 0·5*d*. It is evident that, for some purposes, as for instance in spot-welding, electrical power is much more convenient, while for others where a comparatively large area of metal has to be raised to a high temperature, the use of the gas-jet would be superior in convenience, rapidity, and uniformity.

The emission of products of combustion by the gas appliances would be likely to cause more inconvenience and discomfort than by the corresponding electrical process. There are such a large number of industrial processes for which either of these two sources of heat could be used that it is practically impossible to lay down a general comparison. For most of the purposes of which the Author has had experience, the ratio between the amount of heat required from gas is between 60 and 100 per cent. in excess of that required from electricity, making the nominal efficiency of gas about 50 or 60 per cent. as compared with electricity taken at 100 per cent.

General Conclusions.

The foregoing comparison indicates generally that the cost of most heating-operations is substantially lower by gas than by electrical power at present prices. In the great majority of cases, owing

TABLE XVII.—EQUIVALENT PRICES OF GAS AND ELECTRICITY AT THE VARIOUS ASSUMED EFFICIENCIES. COST OF HEAT ONLY, EXCLUDING VALUES OF SPECIAL FEATURES OF EACH HEATING-AGENT.

Price of gas per therm: pence		6	7	8	9	10	11	12
Equivalent price of electricity per unit: pence		0·205	0·238	0·272	0·306	0·340	0·375	0·41
	Assumed actual efficiencies.	Prices of electricity per unit equivalent to gas at above prices: pence.						
House-lighting	Gas 30; Electricity 3·6 B.Th.U. per candle-power-hour.	1·72	2·00	2·30	2·58	2·87	3·15	3·35
Street-lighting (normal)	Gas 10 ,,; Electricity 2·85 ,,	0·70	0·84	0·96	1·08	1·20	1·32	1·44
Street-lighting (most efficient known)	Gas 10 ,,; Electricity 0·62 ,,	3·30	3·85	4·40	4·95	5·50	6·05	6·60
Domestic water-heating:								
Central boiler	Electricity 100 per cent.; Gas 70 ,,	0·29	0·34	0·39	0·44	0·49	0·54	0·59
Local daily	Electricity 90 ,,; Gas 50 ,,	0·37	0·44	0·50	0·56	0·62	0·68	0·75
Instantaneous	Electricity 100 ,,; Gas Tubular Boiler 80 ,,	0·26	0·30	0·34	0·38	0·43	0·47	0·51
	Gas Geyser 65 ,,	0·32	0·37	0·42	0·47	0·525	0·58	0·63

Space heating :								
Central	Electricity (storage) 85 ,, Gas boilers 70 ,,	0·25	0·29	0·33	0·38	0·42	0·46	0·50
Incandescent fires (total heat) .	Electricity 100 ,, Gas 50 ,,	0·41	0·48	0·55	0·61	0·68	0·75	0·82
,, (radiation only)	Electricity 65 ,, Gas 45 ,,	0·30	0·35	0·40	0·44	0·49	0·54	0·59
Incandescent fires (total heat including ventilation)	Electricity 34 ,, Gas 18 ,,	0·39	0·45	0·52	0·58	0·644	0·71	0·77
Non-incandescent surface (products removed)	Electricity 100 ,, Gas 85 ,,	0·24	0·28	0·32	0·36	0·40	0·44	0·48
Non-incandescent surface (including products)	Electricity 100 ,, Gas 100 ,,	0·205	0·24	0·27	0·31	0·34	0·38	0·41
	Nominal efficiencies: per cent.							
Cooking :								
Oven-cookery	Electricity 100 Gas 57	0·36	0·42	0·48	0·54	0·60	0·66	0·72
Hot-plate cookery	,, 100 ,, 86	0·24	0·28	0·32	0·36	0·40	0·44	0·48
Total per annum for household .	Electricity 100 Gas 67	0·31	0·36	0·41	0·46	0·51	0·56	0·62
Furnace work :								
1,000° F. without regeneration.	Electricity 100 Gas 45	0·46	0·53	0·60	0·68	0·76	0·83	0·91
With regeneration	Electricity 100 Gas 60	0·34	0·40	0·46	0·51	0·57	0·63	0·68
Welding	Electricity 100 Gas 27	0·76	0·89	1·01	1·14	1·26	1·39	1·52

to the absence of products of combustion and the non-material character of electrical power, it is cleaner and more convenient both to install and to use, as well as more efficient in use than gas. In some cases, especially where the character of the heat, the absence of products and the small saving of labour and increase of convenience are not of importance, it is a waste of money to buy a high-grade type of heat for a low-grade purpose. It is only where its superior convenience, cleanliness, and control are of real importance and the financial aspect is less important, that electricity can be preferred to gas on grounds of economy. There are cases where the ease with which electrical power can be switched on and off is of such value that the facility does in fact reduce the total annual cost of electricity for a particular service below that of gas for the same service. In the majority of cases, however, where heat is required the difference in the amount used is not great enough to justify the use of the more expensive fuel on economic grounds alone. The auxiliary use of electrical power for increasing the efficiency of combustion of gas, and for removing the products of combustion, can effect a material improvement in the efficiency of gas-appliances. The commercial hostility between the two industries is so acute at the present time that the use of the auxiliary power in this way is not favoured by the gas industry. It would be of great advantage to both industries, and not less so to the public, if the two were amalgamated. Table XVII summarizes the comparative costs for the various duties which have been considered.

The real question for each consumer is perhaps an individual one, namely, what is the value to the individual purchaser of the superior convenience and qualities of the more expensive form of heat? If that value is greater to him than the difference in the cost of the two fuels then the use of the more expensive source of heat is justified; but where economy is the principal consideration the personal opinion of the Author is that gas will serve for heat-production in most cases, provided adequate care is taken that its dangerous features do not cause trouble.

The Paper is accompanied by five sheets of diagrams, from some of which Plate 1 and the Figures in the text have been prepared.

Discussion.

Mr. S. B. Donkin remarked that it was of great advantage that The Institution was able to discuss such a Paper with the impartiality arising from the fact that it represented all branches of engineering, and held no brief either for the electrical engineer or for the gas engineer. Mr. Donkin.

The Author, in his list of the disadvantages of electricity, referred to the possibility of the generating-station breaking down and causing much greater dislocation than would occur in the case of a failure of the gasworks. That statement, in the main, was true, apart from the fact that the Author appeared to have overlooked the advantages of the Central Electricity Board's connecting lines between selected generating-stations; those lines provided a second source of supply to the generating-stations concerned. That fact should not be overlooked, although it assumed that no two breakdowns would take place at the same time.

The Author had referred to a two-part tariff, with both fixed and running charges, as being applicable in the case of electricity because electricity could not be efficiently stored in bulk. Gas, on the other hand, could be, and was, stored efficiently and economically, and he therefore wondered why one of the London gas companies had recently introduced a two-part tariff. Having regard, however, to the Author's figures for the cost of distribution, he realized that a gas undertaking might wish to save expense by restricting the capacity of its gas-mains. If that could be confirmed by the gas industry it would be a valuable additional contribution.

It would be of advantage if the Author would add a bibliography to his Paper, so that it would be possible to look up some of the references from which he had taken his facts.

Professor W. A. Bone explained that he had not yet had the opportunity of studying the Paper sufficiently in detail to offer criticisms in regard to some of the Author's statements; his general impression was that it contained many statistical arguments and deductions, some of which he would be inclined to question. He had, however, studied one or two of the cases cited in Table XVII, and he did not disagree with the conclusions reached therein. He might, therefore, appear to be in more general agreement with the Author than would be the case if he had had time to make a detailed criticism of the Paper. Professor Bone.

Professor Bone. There was one general point which he desired to make befo putting some questions to the Author. Gas and electricity were t forms of energy, both of which in this country were ultimately deriv from coal. Gas was a form of energy which was derived by ca bonizing the coal at an efficiency of about 80 per cent. when accou was taken of all the products; and although not at high potenti when mixed with air it could be burned to produce a temperatu of up to about 3,600° F. Heat could be produced very cheaply that way, but not energy at high potential. Electricity, on t other hand, was a form of energy which was at a very much high potential than gas, but it was produced with an efficiency at t generating-station of about 25 per cent. at the most. If the t kinds of generation were compared it was found that the ener in the electric current generated from a given amount of co consumed in a power-station was about equal to the energy in t gas produced in a gas-retort from the same amount of coal, wh all the available coke after firing the retorts, as well as the tar b products, had to be credited to the carbonizing process.

If there were a unified authority, having full control of both ga works and electric power-stations, for supplying energy to t inhabitants of Greater London, he thought that it was true to sta that the whole of the heat-energy requirements could be generat and supplied in the form of gas more cheaply than in the form electricity. In that case, however, electricity would be generat only for the highest potential requirements, and a proper load-fact could not be obtained for the generating-station. It would therefo become a question of what proportion of the heating requireme of the area ought to be allowed to electricity, in order to secure good load-factor for the power-station.

He wondered whence the Author had obtained the figures capital costs shown in Table I of the Paper. About a week befo he received the Paper he had been studying the last Report of t Electricity Commissioners, and he found that, taking all t authorized generating undertakings in Great Britain, for the ye ending 31st March, 1933 (the last for which figures were give the fuel-costs per unit were given as 0·137*d*., and all other costs 0·077*d*., which, excluding capital charges, came to 0·214*d*.; t was not very different from the Author's figure of 0·22*d*. It w not quite clear what the Author meant by the net cost of co because the average figure in the Report of the Commissioners w 0·137*d*. The Author, however, gave a figure of 0·103*d*. for "Inter and depreciation on capital, etc.," and then gave a figure of 0·32 as "Gross cost at works." The Commissioners, on the other ha gave the total amount of capital expended in these undertakin

and they said that roughly one-third was for generation and two-thirds for distribution. Taking 10 per cent. on the one-third of the capital applicable to generation, he arrived at a figure of 0·281*d*. If the cost at the generating station, including interest and depreciation on capital, were taken as 0·6*d*. per unit, and 7½ per cent. were added to that figure in respect of the capital applicable to distribution the total cost per unit would be 1·28*d*. Another point which was not referred to in the Paper was that the average loss in the distribution of electricity was about 18 per cent., as, according to the Commissioners' figures, only 82 per cent. of the current sent out of the station reached the consumer. Professor Bone.

He had dealt with the question of capital charges[1] in a recent article. In that article he stated that, if interest charges were taken on a 5-per-cent. basis in respect of the heat-energy supplied to the public by both gas and electricity undertakings, it would be seen how very favourable they were to gas. On such a basis the average interest-charge per ton of coal carbonized at British gas undertakings was 116*d*., and as the potential therms sent out from it were 150 as coke and 75 as gas, or a total of 225, the interest-charge would be practically ½*d*. per therm if spread over the whole of the heat-production or, if charged on the gas alone, 1½*d*. per therm. On the same basis, the average interest-charge per ton of coal consumed in British electricity undertakings was 348*d*., and, as the potential heat in the current generated from that ton was equivalent to 75 therms, this meant an equivalent interest-charge of 4·64*d*. per therm. Therefore the interest charges on capital, taking the interest at 5 per cent. (and with any other rate of interest the proportion would be the same) would be three times as much for electricity as for gas, even if all the interest were charged against the gas and none against the coke and by-products.

Having studied the question for many years, he believed that, from the point of view of the use of the coal-resources of Great Britain, most of the energy to be distributed for heating-purposes should be generated as gas. Were it not for the necessity of obtaining a satisfactory load-factor for electric power-stations, which was all-important as electricity could not be stored, there would, in his opinion, be no justification for the use of electricity for heating-purposes in the great majority of cases. He did not think there was much justification, except on the question of load-factor, for burning coal at a power-station, generating electricity, and then reconverting it into heat.

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[1] "Gas or Electricity for Domestic Heating ?," *Nineteenth Century and After*, vol. cxvii. (1935), p. 712.

Dr. Fishenden.

Dr. MARGARET FISHENDEN said that she did not find the Pa
very provocative, because it consisted so largely of plain stateme
of fact. The Author, however, seemed to set out to make a gene
comparison between gas and electricity, and very soon found t
the conditions were so complicated that the two agents could
be compared in any general way. It was not possible to state i
few words or in any general expression how much cheaper or dea
gas was than electricity. That did not mean, however, that it
not possible to get very good comparisons in particular cases ; a
the information which the Author had gone to so much troul
to give in his Paper would be helpful in making those compariso
for particular cases.

She thought that a simple way of looking at the matter
from the point of view of initial coal-consumption. The efficien
of generation of electricity from coal might be taken as 20 per cen
and the efficiency of production of gas from solid fuel as 50 per cen
because from 100 therms in coal approximately 25 therms in
and 50 therms in coke were obtained, and, if it were assumed t
the coke was equivalent to coal of corresponding thermal value, th
25 therms of gas had been produced from the 50 therms in so
fuel, which was an efficiency of 50 per cent. Hence, for
same initial coal-consumption electricity had to be five times
effective as coal and gas twice as effective ; or, comparing
and electricity, electricity had to be two-and-a-half times
effective as gas.

If the comparative costs were considered, there was a still grea
discrepancy in cost between coal on the one hand and gas or el
tricity on the other, because of the additional costs of producti
and distribution. Taking average prices, such as coal at 45*s*.
ton, gas at 9*d*. per therm, and electricity at 1*d*. per unit, heat
gas cost about five times as much as in coal, and heat in electric
about fifteen times as much, so that in order to cost the same
the consumer gas had to be about five times as effective as c
and electricity about fifteen times as effective.

Those figures showed what a long way electricity had to go
be able to compete with coal, or even with gas. At ⅓*d*. per u
electricity cost the same as gas, and, as was well known and
the Paper proved, in some cases a higher price could be count
balanced or even over-balanced by the increased efficiency possi
with electrical apparatus. For heating-purposes the portability
electrical appliances was probably their greatest advantage.

The only other point on which she desired to touch was
question of the distribution of heat, to which the Author refer
on p. 254. There was, however, an aspect of that question wh

she thought had not received sufficient prominence. The Author Dr. Fishenden. pointed out that many heating appliances did not give a uniform distribution of warmth over a room. There was, however, another very important point to be taken into account, namely, the distribution of the heat over the human body. It did not follow that, because two appliances gave the same total amount of heat, or even because they gave the same proportions of radiation and air-heating, that they would be equally comfortable. If a high-temperature heater of very small area was used when the weather was cold, it was necessary to go so near to the heater that only a small part of the body was warmed, and that part was heated too intensely. That led her to question whether intermittent heating by the usual type of gas or electric appliance could ever be really comfortable in cold weather, and she would suggest to designers of electric heaters and gas fires that alterations might be made in the size and shape of the appliances. In cold weather an intermittently-heated room would have very cold walls, and it was not possible to produce comfortable conditions by the local application of intense heat.

There were two reasons why the open coal fire was so comfortable. One was the gradual heating-up of the room, furniture, carpets and walls, which meant that a smaller intensity of radiation sufficed for comfort; the other was the gradual heating-up of a large area surrounding the fire itself, which meant that the distribution of the radiation over the actual body was more uniform.

Mr. Roger T. Smith remarked that it was impossible to take due Mr. Smith. account of all the items that should be considered for the solution of any one of the problems which the Author attacked. Many of those items were psychological, and one of the merits of his lucid Paper was that the Author stressed the fact that there were so many unknown factors, and gave constant warnings against using the facts given in the Paper without intelligence.

In comparing gas and electricity for the space-heating of buildings, the Author very properly insisted on the importance of ventilation. It had been entirely neglected in many modern flats and offices which were heated electrically; the openings to existing chimneys had been closed, and chimneys had been excluded from the designs of modern buildings. Certain electrical engineers had even gone so far as to boast of having saved the cost of chimneys and flues in buildings that they had equipped. Fresh air was, however, just as important for comfort and for health as warmth, and, even if there were no fire in a grate, a chimney was one of the best ventilators that a room could have, and, when the fire was alight, a small vent high up near the ceiling with a mica flap-valve opening into the

Mr. Smith. chimney-flue was very useful. He ventured to suggest that th 50 per cent. loss of heat up the chimney from a gas fire should no be counted against it, as that effect was in fact one of its greates advantages over electric heating. The Author almost claimed tha under the heading of "Local Heating," but was so judicious tha he did not press the point. He would like to ask the Autho whether it was quite correct, under the heading of "Ventilation, to speak of heat propagated by radiation being taken up th chimney. Radiation heated the objects in a room much more tha it heated the air, which was warmed principally by convectio and it did not seem correct to say that the heat propagated a radiation was subsequently removed by warm air going up th chimney.

There was an incidental heating-effect arising from the use of flue and chimneys, which the Author did not appear to have taken int account. If several flues passed through a partition-wall, when th fires were alight the effect was that of an almost ideal form of pane heating. The only objection to it was that the heat could not b regulated; otherwise it was a fortunate and most pleasant additio to the general heating of a house.

His own conclusions, from his experience and from the presen Paper, were that ideally no one form of heating was sufficient; fo warmth combined with ventilation a fire of some sort with a flu was required, and portable electric radiators of small power, 750 o 1,000 watts, were a very useful addition. If hot-water or stea heating were also available, a combination of all three methods, o at least of two of them, could provide almost perfect space-heatin of buildings.

Mr. Lacey. Mr. Stephen Lacey said that he had had the pleasure of knowin the Author for a number of years, and, as his own work was co nected with the distribution and utilization of gas, he was famili with the subject-matter of the present Paper and also with th Author's earlier publications, which covered very much the sam ground. The rivalry between the gas and electricity supply-compani had applied a stimulus which had been largely responsible for th great advances made during recent years in the design and efficienc of both gas and electrical appliances and also in the service to th public. The Author had suggested that advantages might accru if the two industries were amalgamated. That was a very i teresting point, but it was not suitable for discussion at a technic meeting.

From a technical point of view, the Paper contained so ma figures and statements which called for comment or correction, a perhaps for discussion between specialists, that it was hardly possib

to do more than draw attention to certain points which seemed to be outstanding. Mr. Lacey.

The Author appeared to attach too much importance to the comparative dangers of gas and electricity, and quoted the number of suicides due to gas-poisoning (Table II). In the same Table the Author gave the accidental deaths due to gas and electricity; the Author quoted those figures without comparing them with the total number of accidental deaths, which was 15,829 for the year 1934. Again, after reading the Paper it would hardly be imagined that, if reference were made to the Registrar General's record, it would be found that nine times as many people met their death by accidentally falling downstairs, or elsewhere in their houses, as by accident due to either gas or electricity. In fact, the use of either gas or electricity was remarkably safe, and such accidents as did occur were generally due to badly-designed or improperly-installed appliances, which both industries were doing their best to eliminate.

Mr. Lacey wished to make the most emphatic protest against the Author's statement that the use of gas "gives rise, along with the heat, to the emission of products of combustion which are mainly of a deleterious character." As a general statement, that was quite untrue. The products of combustion of gas were almost entirely carbon dioxide and water-vapour, and the great majority of gas appliances were to-day, and always had been, used without a flue and without any ill-effect to the occupiers of the room in which they were fitted. There were millions of people to-day who used gas for lighting and heating their homes, and the suggestion, made without producing any supporting evidence, that there was something deleterious in the products of combustion was quite unjustifiable.

He agreed with the statement made in the Paper that the hygienic condition of a room was greatly improved by adequate ventilation; in that connection he had listened with great interest to the remarks of Mr. Roger Smith. The provision of chimneys was in general practice the most satisfactory way of ensuring the adequate ventilation of living-rooms, and there could be no doubt that the modern tendency to build flueless rooms was retrograde, and was a false economy. An air-vent was not a proper substitute for a flue.

He did not propose to comment on the question of the relative efficiencies of gas and electricity, as he hoped that Mr. C. A. Masterman would deal with that subject. Mr. Lacey could not understand the details of the capital costs of production and distribution on pp. 218 and 219 of the Paper, to which Professor Bone had already referred. The Author stated that ". . . a gas-main generally costs from three

Mr. Lacey. to five times as much as a corresponding buried electric cable, an from ten to twelve times as much as electric cables suspende overhead," and concluded from this that the capital charge c distribution was very much higher with gas than with electricity Mr. Lacey, however, believed the reverse to be true. In the ca of his own company the capital charge on distribution for the g sold was well under 1*d*. per therm, whereas he thought that tl average capital charge per unit of electricity sold was in the neigl bourhood of ½*d*. It might be that that included other things besid capital charge, but, even if it were only ¼*d*., that was equivalent 7½*d*. per therm. It would therefore be of interest to know how tl Author arrived at his conclusion.

With regard to the cost of production, the Author gave 6·1*d*. p therm as the gross cost of gas at the works, and 0·323*d*. per unit the corresponding cost of electricity. It would seem, however, th that comparison could not be correct, because the average pri of gas to the public was only about 9*d*. per therm, and in son parts of the country it was less than 6*d*.; that was to say, it w sold at less than the figure given by the Author for the cost at t works.

He could understand the Author's difficulty in giving significa figures of cost of production and distribution, because they were greatly affected by the load-factor and by overhead charges. Th fact was generally recognized with regard to the supply of electricit but it also applied to the cost of supplying gas, although to a rath less extent. That was why some gas undertakings had adopt block rates or two-part tariffs. One speaker had suggested th the only reason for a two-part tariff in charging for electricity w the fact that electricity could not be stored, but that was certain not the case; the best-known two-part tariff was that of the Po Office, where the question of storage did not arise. The questi was more one of the relation between overhead costs and the exte of the use made of the service. Such tariffs appeared to be qu equitable and economical, both for the supply-undertakings and f the public, provided that the disparity between the flat rate and t lowest charges did not become unreasonably large.

In conclusion, he did not wish to appear ungrateful to the Auth for the great trouble which the preparation of the Paper must ha involved. It was necessary to remember, however, that the accep ance of a Paper by The Institution, to which both he and the Auth belonged, gave it a currency and invested it with an air of authori which might or might not be justified. That was especially i portant when, as in the present Paper, technical and commerc considerations were so closely associated.

Mr. E. R. Dolby remarked that the heating of buildings had not in the past received very much attention from The Institution. Considering, however, the monumental building over St. James's Park station, as well as the many other large and important all-electric buildings in Great Britain, it seemed clear that in the future the subject would prove of increasing importance to its members. He had therefore read with great pleasure the interesting Paper under discussion. Mr. Dolby.

In the section of the Paper dealing with the thermo-dynamic use of electrical power, the Author foreshadowed a possible efficiency of 500 per cent. Mr. Dolby felt that the Author must be a member of the Magicians' Circle! It would be of the greatest general interest if the Author in his reply would elucidate his statement that, apart from its capital cost, the method was a conceivable future development for the warming of buildings.

He would like to refer to a previous Paper by the present Author which dealt with the heating of the large premises of a firm of drapers.[1] The heating was effected by means of air warmed by electricity and delivered into the building by fans housed on the roof. He would like to inquire whether that installation had continued to give satisfaction, both from the technical and from the financial aspect.

Finally, he would like to allude to *Fig. 4*, in which the consumption of hot water for domestic purposes was dealt with graphically. The results were stated to have been collected from sixty houses in three different districts, and therefore seemed to deserve the most careful consideration.

Mr. J. I. Bernard expressed his appreciation of the Paper, which covered a wide field of specialized applications. In reviewing the Paper and the methods of comparison adopted in it, it might be said that the Author had in some places fallen into the familiar trap presented by an academic comparison of heating-costs based on the potential heating-values of gas and electricity, as distinct from practical working-figures. He had, however, given, as a final comparison under each heading, the practical equivalent costs. Mr. Bernard suggested that it was a little unfortunate from that point of view that Table XVII, which might be read, and indeed had been read that evening, as a final summary of the Author's conclusions, should not give those practical equivalents. With regard to cooking, for example, the conclusion in the text was clearly Mr. Bernard.

[1] "The Electrical Heating and Ventilation of Bourne and Hollingsworth's Premises, Oxford Street." Minutes of Proceedings Inst. C.E., vol. 228 (1929), p. 1.

Mr. Bernard. reached that electricity at 0·7*d*. per unit was equivalent to gas 10*d*. per therm, but in Table XVII various figures were given, rangi from 0·51*d*. to 0·60*d*. per unit of electricity as the equivalent of g at 10*d*. per therm.

The Author had implied that the thermal efficiency of gas-maki was about 80 per cent., but that was only true if full value cou be obtained from the coke and other by-products. The efficiency gas-making *per se* was no higher than the thermal efficiency obtain in the generation of electricity. Further, the coal used by t gas industry was greatly superior to that used by the electric industry, and the use of the higher-grade coal would tend to exhau the coal-resources of Great Britain more than the use of the inferi coal used in electrical power-stations. If, however, the problem coal-conservation was one requiring serious analysis, he thought should be done in terms of the useful service obtained. For examp the coal used for producing gas for lighting was probably five tim as much as that used in generating electricity for electric lamps equal candle-power to the gas burners.

Of the principal advantages of gas, as summarized on p. 223, t second and third should be qualified by a statement of the fact th a sudden increase in the use of gas would produce a drop in pressu which in turn would upset any exact regulation. The statisti of fatal accidents given in Table II were also misleading unless was borne in mind that 75 per cent. of the electrical fatalities to place in factories and similar places, in which gas was not used any extent. If that allowance were made, it would be seen th electricity was much safer than gas in domestic use, as well as f other purposes.

He was glad to see that the Author had assessed the reliabili of electric service more fairly than was sometimes the case. T use of electricity was so popular that the slightest failure of supp became a news-item in the press, whereas statistics showed that t number of interruptions, when expressed in consumer-hours, w an insignificant percentage of the total service given, and was, Great Britain, a much lower proportion than in other parts of t world. In dealing with the principles of comparison it was sat factory to find that the Author, although he had had a much clos connection with the gas industry than with the electrical industr was prepared to give some credit for the advantages in use whi electricity generally had over gas. One of the difficulties which fac the electrical industry was, however, the fact that electricity w nearly always the " second comer," and consequently people did n have so much chance of appreciating the practical value of electri methods.

In the section of the Paper dealing with lighting, he suggested that the Author might have taken some more up-to-date figures. Independent tests of some of the latest types of gas burner had shown consumptions in the neighbourhood of 48 B.Th.U. per spherical candlepower-hour, and the British Standard rating for the smaller-sized electric lamps of 60 watts was $12\frac{1}{2}$ lumens per watt. From those results the figures for gas burners in Table V appeared to be optimistic, and the figures for electric lights pessimistic. Further, with regard to Table IV, the sodium lamp was stated to give 20 lumens per watt; lamps of that type giving 70 lumens per watt had, however, been in commercial production for some time, and experimental lamps had been produced which gave a much greater efficiency than that figure. In regard to street lighting it might be said that the Author's personal preference for gas as a means of illumination hardly corresponded with the great progress which was being made by electric lighting in displacing gas. For example, no less than 330 miles of streets were included in eight conversion schemes which had recently been adopted. Mr. Bernard.

The Author was to be congratulated on the very full analysis of the comparisons for room-warming and water-heating. Although those analyses were probably carried further than anything that had been published before, it was doubtful whether even they reflected all the savings which were possible by means of electricity, as they generally indicated a comparison of about 15 units as being equal to 1 therm of gas, whereas practical experience showed that, if electricity were properly utilized, 10 units might be equivalent to 1 therm.

In connection with furnace-work, the use of gas for industrial heating was discussed briefly in the Paper, and the Author recognized the loss of efficiency which occurred in gas firing when high temperatures were required; but the temperatures which the Author took in Table XVII were not applicable to ordinary furnace-work such as carbonizing and hardening, which required temperatures in the neighbourhood of 1,700° F. For those purposes the relative economy of electricity was evidently much higher than that stated by the Author.

The Paper was mainly concerned with comparisons between units of electricity and therms of gas, but the relative cost was clearly the final criterion for the consumer. The Author made but slight reference to that aspect of the problem, and he was apparently not fully aware of the extent to which the cost of electricity had been reduced in recent years. For example, the price of electricity for domestic purposes had been reduced by more than 50 per cent. in

Mr. Bernard. the last 10 years, and to-day 80 per cent. of the public coul purchase electricity for heating and cooking at $\frac{3}{4}d.$ a unit or less at which price, as the Author showed, electricity was as cheap as ga at 10*d*. per therm.

Lord Pentland. Lord PENTLAND desired to draw attention to one general featur of the Paper which had not yet been mentioned, namely, that th comparison was of necessity made as at the present date, an took no account of the trend in relative costs of the two agents In estimating running costs for any particular installation a engineer would be bound to take into account any probable futur increases or reductions in the tariffs for the two services. Fo example, the supply of electricity was of much more recen development than that of gas, and substantial progress had bee made in the past few years in improving the efficiency of genera tion, distribution and application. Assuming that that progres might be expected to continue in the next few years, the whol comparison would be modified in favour of electricity. An out standing example of such a modification would arise if the heat-pum cycle were to be adopted generally as a heating process. Furthe any substantial increase in the cost of coal might be expected t cause a larger increase in the cost of gas than in that of electricity particularly if the demand for gas-residuals were fairly elastic. A reduction in the cost of coal would have the opposite effect. Th Author made no reference to diversity and load-factor as affectin the costs of gas and electricity. Broadly, it was true to say tha both agents became cheaper as consumption increased, but tha effect was greater in the case of electricity than of gas; firstly because in the case of electricity the capital investment was greate so that the overhead charge to be spread over the units wa greater; and, secondly, because electricity could not be stored, s that diversity was of more importance than in the case of gas. Fo the above reasons, it would be fair to say that in a case where ther was little to choose between the estimated present running cost o electricity or gas, electrical methods would be likely to prove mor economical over an extended period.

He would also like to express his appreciation of the admirabl way in which the Author had summed up the position in th "General Conclusions."

Mr. Grierson. Mr. RONALD GRIERSON remarked that, in spite of the Author' long connection with the heating industry, especially notable for hi invention of the invisible panel warning system, he seemed still t be in a state of philosophic doubt with regard to the relative merit of the various heating agents. It was to be hoped that the discussio that evening would enable the Author to make a final decision on th

subject, so that he might be determined in future to specify electricity as the agent to be employed. Mr. Grierson.

The Author had made somewhat disparaging reference to the low thermal efficiency of electric generation, quoting values of the order of 20 to 25 per cent., but Barking and several base-load stations were now operating at efficiencies of 28½ per cent., and even better figures would undoubtedly be obtained in the near future. It was useless to talk about efficiency at the consumer's terminals. In Barnet gas was being advertised not by the therm but by the "gas unit" of 4,000 B.Th.U., and that was compared with the 3,400 B.Th.U. of the kilowatt-hour. The comparison was misleading, because the potential consumer was not told that he would get only 50 to 70 per cent. of the 4,000 B.Th.U., instead of the 100 per cent. of the 3,400 B.Th.U. which he would get from the kilowatt-hour. Again, the relative cost of the coal used by the two industries should be mentioned, together with the over-all efficiency value between the raw material and the utilization of the agent, because the relative efficiency at the purchase stage was purely an intermediate figure.

With regard to the cost of installation, one authority in London piped a block of eighty-four flats free for gas, but the wiring was paid for at standard rates. Even so, seventy-eight tenants chose to utilize electricity for all purposes, and only six used gas for cooking and heating at the outset, none using gas for lighting. It would therefore appear that in the opinion of the tenants the advantages of electricity completely outweighed all other considerations.

He entirely agreed with the Author's remarks on the appearance of gasholders. Some friends of his had built a house near Richmond; after they had spent a substantial sum on the property, the gas company found it necessary to erect a Falstaffian gas "substation" within 100 yards of the property, with disastrous effects on its value. His friends were so annoyed that they now used electricity.

The Author appeared to confuse the process of storage on site with that of storage at the gasworks, regardless of the pressure-drop in the mains and distributing pipework. Surely he did not mean to infer that the present capacity of gas-mains was absolutely unlimited? A point of saturation of the existing network due to pressure-drop was bound to arise; and gas would then either have to be supplied on an off-peak and peak basis very much as in the case of electricity, or the pressure would have to be raised and governors or reducing-valves provided either for every installation, or for the control of districts.

The Author made several references to flueless gas heaters, which discharged the products of combustion into the occupied room.

Mr. Grierson. Was it to be understood that he really recommended such heate as being hygienic, particularly as he mentioned that they woul inevitably cause excessive humidity?

The most important point which he wished to stress was that national safety, particularly as it had now been found necessary repair the gaps in British defences. He spoke with the experien of one who had been responsible for the maintenance of electric and mechanical services behind the lines in France during the latt part of the War. He had found that the miniature electricity supply "grid," which was intended to stretch ultimately fro Dunkirk through to Bethune and Arras, was practically immu from damage or destruction by bombing. One span had bee brought down by an intense bombing attack, but it had been restore in about three-quarters of an hour; yet that was during the inten bombing of the back areas in early 1918. He felt, therefore, th the Central Electricity Board had rendered an invaluable service the defence of the country by inter-connecting all the power-station so that if by bad luck any of them were bombed the supply could maintained. It could not be overlooked that gas lighting of railwa rolling stock was being eliminated, because accidents in the pa had often been followed by fire due to ignition of the gas. T devastation wrought by the gas explosions in the old Post Offi tube in December, 1928, might also be mentioned; it indicated t nature of the damage which might be done if London were bombe At the time when the Post Office tube blew up the gas-mains cou only be cut off by digging holes in the road, drilling holes in t pipes, inserting bladders in the pipes, and inflating them. Had t gas undertakings developed any better methods of control? another war broke out it would be a very different affair from t last one, and he felt that the risk of escaping gas being ignited incendiary bombs could not be overlooked. In the event of an a raid alarm, what would happen if the gas supply of a large to were shut off in order to ensure a 100 per cent. black-out, and th restored at short notice?

With regard to accidents, he thought the proper criterion w not the number of installations but the number of people dai associated with the innumerable uses of electricity. He ventur to submit that the users, as distinct from the registered consume of electricity vastly outnumbered the users of gas, and, viewed that way, the statistics quoted by the Author would assume entirely different aspect.

The Author stated that the observed cost was always a functi of the efficiency, but it might be asked whether a Savile Row s was essentially inefficient compared with the products of a fif

shilling tailor. There was a very extensive market for the more costly products because they were more effective. Mr. Grierson.

Like the Author, he had been attracted by the possibilities of the heat-pump, and he had studied the system very closely in connection with a town-hall building in London, for use in conjunction with an invisible ceiling panel-warming system and an air-conditioning plant, the heat being "pumped" from the atmosphere. Although a heat-pump plant absorbing 400 kilowatts would do the work of a 1,000-kilowatt electrode boiler, and would therefore show an apparent efficiency of 250 per cent., the scheme proved to be impracticable at the present time. Instead of the relatively simple and straightforward electrode-boiler and its control-gear, the heat-pump plant would include ammonia-compressors absorbing about 240 B.HP., a 20-B.HP. fan designed for a duty of 70,000 cubic feet per minute, and an air-cooler containing some 4½ miles of pipes, which would possibly have to be duplicated to allow for de-frosting periods. The temperatures at which the plant would operate precluded the possibilities of thermal storage, so that a peak-load charge of £5 per kilowatt for 400 kilowatts, or £2,000, was involved, plus the metered charge for all units metered. During the off-peak periods 2,000,000 units could be purchased for the amount of the fixed charge alone; labour-charges still remained to be added, and duplication of plant seemed essential to guarantee continuity of service, so that the scheme was dropped. Those who were familiar both with refrigerating-plant and electrode-boiler plant would not hesitate for a moment to say which scheme was the simpler and more likely to give satisfaction, although there were distinct possibilities for a combined swimming-pool and ice-rink plant, which would be used for freezing in winter and for warming the water in summer.

With regard to gas lighting, the Author did not appear to have stated the cost of the motor-driven fume- and heat-extractors which were considered by the managers of gas showrooms to be essential for the well-being of the decorations and of their customers and staff. Again, it was the effectiveness of electricity that dominated the position, and it was the smell, risk of explosion, poisoning, excessive humidity, increased maintenance-cost and risk of derangement which were such severe handicaps to gas undertakings in the sale of their products.

He could not accept the Author's figures for the effectiveness of the lagging of electric water-heaters; in his opinion the heat-losses given were at least 35 per cent. too high. With regard to daily efficiency, in a paper [1] read before the Institution of Electrical

[1] R. Grierson and D. Betts: "The Electrical Warming of, and the Supply of Hot Water and Conditioned Air to Large Buildings," Journal Inst. E.E., vol. 76 (1935), p. 461.

Mr. Grierson.

Engineers Mr. Grierson had suggested that 2½ usages per day wa normal for cylinders that were intelligently selected with referen to the probable demand, and that figure was confirmed in th discussion on that paper.

Mr. Nobbs.

Mr. W. W. NOBBS remarked that the subject covered by th Paper was so extensive that few people could have an intima knowledge of every phase of it; his remarks would be confine to those portions of it on which he could speak with authorit He was in entire agreement with the Author regarding the funda mental differences between gas and electricity as agents for hea production, and the Author was to be congratulated on the mann in which he had set out the advantages and disadvantages of the tw agents. So far as his own experience of heating and hot-wat service went, he was in general agreement with the Author's co clusions. Expert opinions had already been expressed on th subject of capital costs of generating plant and distribution. H thought that, in general, the Author had been lenient in putting th cost of installing electrical fittings at from three to five times th of installing gas equipment. His experience was that the high figure was nearer the mark, but a great deal depended on th particular conditions applying to each individual installation.

A criticism which applied generally to the examples given in th Paper was that they were too extreme. Doubtless this was t emphasize the Author's points, but they might be accepted a conditions generally encountered in normal practice. He woul suggest, for instance, that a 20-gallon bath drawn off in 6 minute requiring a power input of 30 kilowatts or a gas-consumption at th rate of from 200 to 250 cubic feet per hour, would be more co vincing and applicable to actual requirements than the exaggerat example given by the Author of a bath requiring 20,000 B.Th.U namely, 40 gallons of water, drawn off in three minutes; there we thousands of gas and electrically-heated instantaneous wat heaters with practical ratings which gave reasonable satisfactio He would also suggest that the first item in Table VI, the "ve full hot bath," might have been omitted with advantage, or the ra reduced to more reasonable proportions. Adopting the temper tures used later in the Paper, that item inferred a 40-gallon bat 30 gallons being heated to 130° F. and then cooled to 110° F. by th addition of 10 gallons of cold water; a bath temperature of 110° was too hot for the great majority of people. For much the san reason, he could exclude the last value given in Table VII; su an extravagant demand as 50,000 B.Th.U. per person per day f domestic hot water should not be countenanced by statistic reference. He thought that all the thermal demands noted in Tab

VII, except that for a poor person, were rather exaggerated; this view was borne out, so far as it was applicable, by *Fig. 4*. If the latter were studied and compared with Table VII, the impracticability of applying general conclusions to individual cases without making provision for special conditions would be manifest. In his experience the most extravagant users of domestic hot water were the occupants of residential flats where a constant hot-water supply was available, but even in such cases he had found that a normal demand was met by the provision of some 25,000 B.Th.U. per person per day, and he would put the high value in Table VII at 30,000 B.Th.U. In other types of buildings the values would be correspondingly less. Mr. Nobbs.

Dealing with central heating, the Author put the primary efficiency of the conversion of electrical energy into heat at substantially 100 per cent., and for a gas-fired boiler at 80 per cent. The Author also put the efficiency of the whole boiler-installation, taken from heating-agent to water, at 85 per cent. for electricity and 70 per cent. for gas; namely, a further loss of 15 per cent. for electricity and 10 per cent. for gas. Since the installation, apart from the boiler-plant, was identical, it seemed necessary to account for the difference in the two figures. He would not have thought that the thermal-storage vessels, when carefully coated with heat-insulation material, would account for that 5 per cent. additional loss. The Author appeared to overstress the possible dangers of an electrical installation, saying that it ". . . might cause the immediate death of any person touching a piece of live metal." In a thermal-storage plant of the character under discussion the only pieces of live metal were the busbars, suitably guarded behind the switchboard, and the electrode-terminals, which were protected by a guard which could not be removed without automatically opening the main circuit-breaker.

In dealing with the distribution of heat, the Author referred to the hygienic disadvantages of electrically-derived heat in not requiring any ventilation, and he referred to the more pleasant conditions existing where a gas fire with a large flue caused the air in the room to be changed from five to ten times per hour. Except for lavatories, kitchens and similar rooms, that was a high rate of ventilation, and any ventilation-effect exceeding six changes an hour in a private room would render it uncomfortable.

Table XVI gave the results of experiments with different rates of ventilation in a room with a volume of apparently 2,000 cubic feet. Those results were exceedingly interesting, and would be even more so if the Author had been able to provide more data on which an analysis could be made.

Mr. Masterman. Mr. C. A. Masterman said that the Author made repeated refer- ences to an imaginary low efficiency of gas appliances, which h variously attributed to heat-losses in the flue, inadequate insula- tion, ventilation of the room and other causes, and in *Fig. 2* h referred to the supposed losses; but whereas the ordinates i *Fig. 2* extended to 3,750° F., experience showed that from 500° F to 600° F. was the maximum for domestic appliances.

The Author's intention appeared to be to compare gas an electricity for equivalent services. Many of Mr. Masterman' criticisms of the Paper arose from his disagreement with the Author' assumptions that he was setting out equivalent service-condition The only essential contrast between the two agents was that a ga appliance had to vent its products whereas an electric appliance coul in some circumstances remain sealed. The significance of the heat loss from a gas appliance due to that venting had been greatl decreased during the last few years owing to technical develop- ments. Heat-loss from the flue of the ordinary domestic gas ove was now approximately half what it had been a few years ago, an was a fraction only of the loss through the lagging, which was c similar magnitude whether the cooker were gas or electric. It wa interesting to remember that designers of electric cookers had no come to appreciate the need for venting the oven in the interests c good cooking, and that with modern cookers for equivalent cooking service the loss in weight of the foodstuffs cooked was substantiall the same for both gas and electrical cookers.

The Author stated that by the agency of electricity "... pur heat-energy can be delivered through flexible wires in any quantity ..." That claim the electrical engineer would be the first t contradict, since it was the limitation of supply which, after pric was one of his greatest handicaps.

In connection with water-heating, the most common applicatio of gas was by means of an instantaneous water-heater, a system i applicable in the case of electricity, since it would involve a loadin of the order of 25 kilowatts. Similarly, the relatively slow operatio of the electric hot plate was partly due to the limitations in loading which corresponded to very little more than half the heat-energy i a normal gas-ring. Even so, the switching on of all the elements c an electric cooker corresponded to bringing into simultaneou operation more than twenty electric lamps. By turning down th gas supply to correspond to the heat-input of an electric hot plat an increased efficiency was obtained, but most users valued th advantage of speedy operation, even at a slight increase in relati gas-consumption.

The Author referred to the use of gas geysers as involving conside

able risk of accident, a claim which could hardly be reconciled with the many tens of thousands of those appliances which were in daily use, and with the fact that fatalities from such appliances in five centuries would be less than the annual fatalities from road accidents in Great Britain. Mr. Masterman.

The Author suggested that carrier-current control was peculiar to electricity, and suggested that gas was, in its nature, not susceptible to anything resembling this control. He was apparently unfamiliar with the fact that a number of cities, including Berlin, were largely lighted by gas all of which was under pressure-wave control.

The Author propounded the theory that if the products of combustion exceeded 212° F. condensation could not take place. Although perhaps of no great significance, that theory was wholly incorrect. It was a familiar fact that in many water-heaters, for instance, the products of combustion might be leaving the flue-outlet at from 300° F. to 400° F., yet condensation might occur and might be a nuisance.

Reference was made in the Paper to a reversed refrigerator-cycle as a means of heating. That was an interesting device which within a limited field had been successfully used, but it was a device which no electrical engineer would claim as peculiar to electricity.

Detailed comment upon the Author's references to lighting would perhaps be inappropriate, but his conclusions seemed to be incompatible with his own claim that gas was a cheap lighting agent, and with the experiences of the Gas Light and Coke Company, which reported a substantial addition last year to the number of gas street-lamps put into operation. The Author might be interested to learn that the average life of their mantles was not, as he had suggested, about 350 hours, but over 1,000 hours. In selected cases mantles had been found to give full light-value after 8,000 hours.

The Author's calculations of equivalent prices for gas and electricity for water-heating appeared to credit gas with a heat-transfer efficiency of under 60 per cent.; in Mr. Masterman's opinion that was an under-estimate of about 20 per cent. It should be emphasized that, apart from the difference between gas and electricity in heat-transfer efficiency, there was no reason for any contrast in operating efficiency. It would be interesting to have the Author's explanation of his statement that a gas heater could not be so perfectly insulated as an electric heater. The Author's reference to the deposition of fur as being responsible for substantial reductions in efficiency in the case of gas-fired water heaters was not supported by evidence and experience. If pilot-lights existed which burnt about 1 cubic foot of gas per hour, that would represent a degree of waste if the heat were in no way utilized; in practice, however, the normal rate for a

Mr. Masterman. pilot-light was of the order of 0·5 cubic foot per hour, and recen developments in pilot-light design suggested that an even lowe consumption could be obtained without prejudice to stability The Author's claim of 10*d*. per therm as equivalent for water-heatin to 0·7*d*. per unit was approximately 50 per cent. in error, the electrica equivalent in fact being considerably less than 0·5*d*. per unit.

The Author's comparison of the two heating-agents for room heating appeared especially to invite the criticism that he wa comparing unlike services. If the Author were content wit "stuffy" room-conditions, due to inadequate ventilation, the comparisons must be based on flueless electric heaters against flueles gas heaters, both types of appliances being now very familiar to th public. It would then be found that the equivalent of gas at 10*d* per therm was electricity at about $\frac{1}{3}$*d*. per unit. It would b generally agreed, however, that such a form of heating fell short o the ideal, and that, for conditions of true comfort, ventilation a well as heating was required.

The Author contrasted the ventilation from an ordinary 9-inche by 9-inches flue with the smaller types of proprietary flues used fo gas fires. The measurements given in the Paper were incorrect; th dimensions of those flues were 12 inches by 2 inches, or 15 inches b $2\frac{1}{2}$ inches, and not, as the Author stated, 10 inches by 2 inches. very complete series of tests and calculations with such flues had le to the conclusion that, for a 30-foot chimney a 9-inch by 9-inch flu with a 5-inch chimney-pot would give 7,000 cubic feet per hour c additional ventilation; a flue 15 inches by $2\frac{1}{2}$ inches would give 6,00 cubic feet, and a flue 12 inches by 2 inches nearly 5,000 cubic fee The Author in the following pages appeared to suggest that th ventilation in the former case was wholly excessive, whereas in th latter the ventilation effect was negligible. In disregard of thos figures, however, the Author had assumed that, with a gas fire a air-exchange of 10,000 cubic feet per hour took place, for the heatin of which he had made an allowance of 25 cubic feet of gas. Suc an allowance would lead to a temperature rise in the air exceedin 60° F., and would be intolerable to the occupants of the roon The Author's Tables, derived on that basis of calculation, appeare to be wholly misleading, and Mr. Masterman considered that th principle from which they were derived was false, since the warı vitiated air which passed up the chimney had already served i purpose; on hygienic grounds it was therefore desirable to remov it from the apartment.

In Table XIV there was a column representing the running cos for an electric fire, based on a radiant efficiency of 100 per cen An efficiency of even 98 per cent. could not be obtained with a surfac

temperature of less than 1,650° C., which was not only impossible to obtain but would also be intolerable in effect, even if dark glasses were worn. Mr. Masterman.

The Author estimated that electricity at 0·7*d.* per unit was equivalent to gas at 10*d.* per therm for cooking. That estimate appeared to be approximately 50 per cent. in error, and he could only imagine that the Author had not made himself familiar with the developments in gas-cooking which had taken place over the last few years; or perhaps that the Author had exaggerated the developments in electric cookers. Inadequate information must have controlled the Author's reference to gas and electric furnaces. The Author's broad statement that the outside of an electric furnace was cooler than that of a gas-fired furnace seemed also to be based on an irresponsible estimate.

He would be the last to claim that any one form of heat-energy was ideal for all types; undoubtedly there were circumstances where electrical heating was truly economic. He believed, however, that there were many more applications for the use of gas. Industrialists were certainly recognizing that the higher throughput and smaller wastage obtained with readily-controllable fuels would often more than offset the higher price of the crude heat. The Author's suggestion that developments in thermal equipment were handicapped by unwillingness on the part of either the gas or the electrical industry to take advantage of the facilities provided by the other was quite unfounded.

The ground covered by the Author was important, and his Paper was of a type unusual to The Institution; it was all the more necessary, therefore, to draw attention to an undue number of apparent inaccuracies and to the possibility of the Paper creating false impressions detrimental to both the industries concerned.

*** Lieut.-Commander R. B. Fairthorne observed that, in Table XVII, opposite "Hot-plate cookery," comparative figures were shown indicating for electricity a superiority in assumed actual efficiency. This seemed at variance with the statement on p. 262 with reference to comparative heat-absorption from the surroundings. Lieut.-Commr. Fairthorne.

Did not the Author wish to convey that there was a variable efficiency in the case of an electrically-heated hot-plate, which overtook that of its competitor only after a lapse of time had allowed the temperature to rise?

If that was so, he would ask the Author whether the figure for electricity in Table XVII represented the maximum or the mean

*** This and the succeeding contributions were submitted in writing.—Sec. Inst. C.E.

Lieut.-Commr. Fairthorne. efficiency. Did it take into account the fact that " . . . the tim occupied . . . with electric power is 70 per cent. greater than witl gas" ?

Mr. Humphreys. Mr. O. W. HUMPHREYS observed that the Author was to be con gratulated on his attempt to settle the long-standing controvers concerning the relative costs of gas and electricity for the purpos of heat-production. He had read through the Paper with con siderable care, and had noted the very fair and impartial way i which the Author had enumerated the relative advantages of th two agents for heat-production ; he found it difficult to follow him however, on the question of the determination of costs in connectio with incandescent fires, and on most of his remarks concernin cookers.

The question of the allowance necessary for ventilation i comparing the costs of heating by gas and electric fires was admittedl difficult, but there seemed to be little justification for compariso on a basis of equal ventilation. If, as the Author implied, tw changes of air would in general be adequate for a room of 2,000 cubi feet, the additional three or more changes produced by gas fire might lead to a feeling of slightly greater freshness, but they coul not be given any monetary value. He suggested that the faires comparison would be on the basis of the consumption of gas o electricity necessary to produce certain specified minimum condition of temperature and ventilation. If two changes of air per hour wer specified as a reasonable figure, it was clearly unfair to debit th electrical system with five changes merely on the grounds that ga could not heat the room with less changes. The cost of electricit and gas should be assessed on the basis of two and five change respectively and the additional sense of freshness, or the increas in draughts, which resulted from the greater ventilation given b the gas fire should be allowed for when the incidental advantage and disadvantages of the two forms of heating were considered As the Author stated, the use of a fan to assist ventilation in privat houses and offices was rare. Neither was it necessary. Force ventilation had its undoubted advantages, but if natural ventilatio sufficed during the summer months for the room that, in the winte was heated and ventilated by a gas fire, there would appear to be n reason why the same system should not be employed throughout th year in the case of an electrically-heated room. He therefor suggested that to obtain a fair estimate of the relative costs whic were to be expected in practice under the general conditions postu lated by the Author, allowance should be made for five changes o air per hour in the case of a gas fire and two changes in that of a electric fire, no fan being considered in either case. If Table X

were adjusted accordingly, it would be seen that equivalent prices, including the provision of adequate ventilation, would be very nearly 1*d*. per unit for electricity compared with 10*d*. per therm for gas. That proportion agreed closely with the experimentally determined figure which the Author stated on p. 259, but to which no reference was made in Table XVII. Mr. Humphreys.

With reference to cooking it was stated on p. 262 that "the time occupied . . . with electric power is 70 per cent. greater than with gas." The Author must, he thought, have intended that statement to be limited to hot-plate cooking, for apart from preheating, which was admittedly quicker with gas, there should be no difference in the speed of cooking in an oven, and electricity was certainly as fast as gas for grilling purposes. Was the Author aware that several manufacturers were to-day producing, in very large quantities, electric hot-plates which would boil 2 pints of water (a temperature-rise of 85° C., with flat-bottomed utensils) in about 6 minutes, and 3 pints in 8 minutes?

It was difficult to follow the Author in his contention that a cook understood a gas cooker more readily than an electric one, for the keynote of electric cooking was its simplicity. With a gas cooker, owing to fluctuations in gas-pressure and fouling of the burners, there was no permanent relation between tap-position and height of flame, whereas with an electric cooker only three switch-positions were provided, and in practice only two of those were generally required. Control was so simple that, although thermostats were fitted to gas cookers some years ago, there was as yet no indication that a demand for such assistance would arise from users of electric cookers.

In connection with cooking-utensils, it was true that, with one widely-used type of electric hot-plate, exceptionally fast boiling could be obtained by the use of flat-bottomed vessels. It was, however, very misleading to claim that their use was essential, as the majority of the users of this type of hot-plate were so satisfied with the performance obtained with ordinary utensils that they did not take advantage of special utensils. Further, so far as other types of electric hot-plate were concerned, flat-bottomed utensils offered no advantage whatsoever. In fact, the shortest boiling-times were frequently obtained with the ordinary vitreous enamelled-iron ware.

Concerning the cost of cooking, the Author stated that "In a prolonged series of trials . . . the amount of heat used in a gas cooker was from 50 to 100 per cent. greater than in an electric cooker," and in the next paragraph that "The relative cost of gas and electricity, taken over a long period, was found to be that electricity at 0·5*d*. per unit is the equivalent of gas at 10*d*. per therm."

Mr. Humphreys. On the basis of the Author's own tests, the equivalent price fo electricity was, he believed, from 0·51 to 0·68 pence per unit, or a average of 0·6*d*. per unit. In view of the material improvement i the efficiency of electric cookers which, according to the Author, ha taken place since the experiments were made, the figure of 0·7*d*. pe unit, which he derived by calculation for modern cookers woul appear to be too low. In any case, the inclusion in Table XVII o figures for cooking which the Author admitted to be out of date was of questionable utility.

In the last paragraph of his conclusions, the Author must, h thought, have been chiefly concerned with the dwellers in sma towns and rural areas. On the basis of the relative costs whic the Author had put forward, very large numbers of consumers i and around the larger towns and cities were now buying electricit at prices which made it as cheap as, or cheaper than, gas, for purpose of heat-production. Their number was still further increased, if hi deductions from the Author's statement with reference to in candescent fires and cooking were warranted.

Mr. Ryves. Mr. Reginald A. Ryves drew attention to the words on p. 25 " . . . some convention in regard to the loss of heat through the exces sive ventilation that is induced by a gas fire," and observed that, a relating also to the efficiency of a coal fire, consideration should b given not only, as the Author seemed to assume, to that efficienc in respect of the room, but also to efficiency in respect of the hous or to a room above it; the loss of heat, in that separately-considere computation, being measured at the chimney-pot. The heat tran mitted by the column of air and gases in its passage through chimney that presented from 100 to 140 square feet of lining wa considerable and, per degree of rise of temperature, was of speci importance, in that it reduced, in the upper storey, depreciatio of the fabric of the house, the interior decoration (especially wal paper), furniture, fittings and clothing. That was due to the effe in maintaining the temperature inside the house at a level slightl above (or less below than it otherwise would be) the air-temperatu outside; the result was that when warm and moist air penetrat a house which had been chilled by a previous cold spell, the co densation of moisture on the walls, ceilings, and contents w considerably reduced, or even prevented, during the critical peri which elapsed before the colder parts of the house attained t temperature of the outside air.

Mr. Verity. Mr. C. E. H. Verity stated that, whilst appreciating the gre amount of trouble that the Author had taken in evolving a theoreti basis for comparison, he was disappointed to find frequent statemen that the conditions were so variable and the information availa

so incomplete as to render any comparison only a first approximation. Mr. Verity. It appeared that the problem was rather more of a domestic one, and one that did not admit of detailed theoretical treatment, as the comparison was necessarily influenced by such matters as convenience —such as the use of electric light, æsthetic values—such as the preference for coal fires, and speed—such as the rapid heating of a gas cooker.

The Author tended to take the attitude that there was considerable rivalry and competition between the producers of gas and electricity, and referred to the commercial hostility between the two industries as being very acute. He thought that that was not the right attitude to adopt and that the two agents for the production of heat should be considered as complementary rather than as competitive, as there were many more important considerations than either the pure financial aspect or the relative efficiency of the processes.

It would be of assistance if the Author could give typical comparative heat-balances, indicating the losses incurred in the production of gas and electricity from 1 pound of coal of given calorific value, together with corresponding typical financial balances.

Considering the matter from a more national aspect, he suggested that the Author might show how the initial fuel could be most usefully employed in producing the various products required throughout the country, such as gas, electricity, coke, tar, oil, and petrol. There must be an optimum financial condition which would give the cheapest production of all those items in the proportion in which they were required by the general public.

The Author, in reply, ventured to deprecate the introduction into The Author. such a discussion of the "back-chat" that often figured in similar discussions in the technical press, as he had hoped to keep it on a somewhat higher plane. It was even less edifying to hear two great industries sneering at one another than to hear individuals indulging in personalities in public. The gas-holder was not an object of beauty, but neither was a row of pylons sprawling across a beautiful countryside; a heated argument as to their relative ugliness did not in any degree influence the user in deciding whether gas or electricity was the better for doing his work. There had also been mutual recriminations as to the degree of danger. As if to illustrate the observations made in the Paper and also the incongruity of such recriminations between the two industries, the daily press of a few days later gave an account of an accident in Leicester where three hundred people were driven out of their homes by an explosion due to a gas-leakage, and side by side with that account was another of an electricity breakdown in Bradford which stopped the whole of the supply to that large town for at least 24 hours. The use of

The Author. any such agent inevitably involved a certain degree of danger, bu as Mr. Lacey had said, it was singularly small.

Compared with electrical energy any gaseous fuel had certai disadvantages and dangers, while high-grade energy like electricit could not be otherwise than expensive and liable to accident, an an argument on the question of which of those features was the mor undesirable was not very edifying. The truth was that bot electricity and gas were indispensable, and it was necessary to pu up with the small disadvantages which their use involved. Bot had drawbacks, some of which were inevitable. Those which wer not inevitable should be remedied in the public interest. The objec of the discussion was to help the public to choose with intelligenc which was better in the circumstances for any service in whic either could be used. There were examples in the discussion o distortions of the very careful language of the Paper and of mis-representation of the figures given, with the object of scoring point in the interest of one industry or the other; it was difficult to se why such distortions should have been made.

Hardly any of the criticisms of the Paper were directed to it fundamental essence, but were largely on the accuracy of the figures which were given in the earlier part of the Paper relatin to the cost of the plant and of the generation of the two agents and also to the values given for the various efficiencies. Tw important facts seemed to have been overlooked by the majorit of the speakers, namely, that the first class of figures was prepare solely for the purpose of giving persons unfamiliar with thos matters a general idea of the approximate cost of the plant an of the generation of the two agents, and not with the impossibl object of laying down in a sentence complicated figures of universa application. Any one who studied the extremely involved publishe figures relating to the cost of the different power-stations and gas-works must have been struck by the wide variations between them according to the cost of the land, the type of machinery installed the quality of equipment and other features having little relatio to their maximum output. In the same way the cost of supplyin and laying cables and gas-pipes varied greatly between differen cases. In a general Paper it was totally impossible to ente into a long explanatory discussion on those extremely intricat matters, and it would not be of the slightest use to an averag reader of the Paper, who required only a general approximat idea of the magnitude of those costs, if it could be obtained It seemed to have been overlooked that the precise accuracy o figures prepared for such a purpose, even if attainable, would hav

been of quite secondary importance to the main object of the Paper, and hardly worthy of the prominence given to them in the discussion. The Author.

Similarly, a good deal of criticism had been directed from one side or the other against the values of the efficiencies given. Those criticisms largely counter-balanced one another. Such electrical authorities as Mr. Bernard complained that the Author had not been fair to electricity, while Mr. Masterman complained that the Author had not been fair to gas. Similar discrepancies were observed in regard to lighting efficiencies. It should have been perfectly obvious that, as the efficiencies of different makes of plant varied between themselves, and in a growing industry were continually being improved, the best values of to-day were likely to be better in both cases than those of yesterday, so that it was impossible to lay down any absolute values for permanent use.

Mr. Lacey had properly called attention to the fact that the acceptance of a Paper by The Institution invested it with an air of authority, which possibly in the present case might not be justified. The latter reservation was perhaps understandable from the point of view of gas, but he cordially agreed with the preceding remark. The language of the Paper and its statements had been accordingly prepared with the greatest possible care and in full appreciation of the fact that the subject dealt with involved large commercial interests. In spite of what had been said in the discussion he did not see any reason for withdrawing or even modifying any of the figures given in his Paper, which he knew were substantially correct.

The question had been raised as to the source of the various figures of the cost of generation and distribution and as to how they had been determined, and an explanation seemed necessary. He had re-examined the original calculations from which the figures had been drawn up when the Paper was first drafted, and had found the following explanations :—

The total recorded cost of a number of large generating-stations was obtained from various published sources of which he had now no record, along with their total kilowatt-capacity ; among others, particulars of the following stations were obtained :—Bristol, Newcastle, Brighton, Tonbridge, Glasgow, Tunbridge Wells and Hackney. The total kilowatt-capacity was then reduced to the equivalent of therms per hour, and a simple division gave the figures in the Paper ; the highest and the lowest of those were given, the remaining figures varying between those two extremes. It would be observed that in each case the total capacity of the equipment had been con-

The Author. sidered, and not the actual output. There had been great difficult in obtaining any figures whatever relating to the cost of pip and cables; nothing could be found in published records and n particulars could be given by either of the industries. The Autho had applied to many engineers, including his friend Mr. Stephe Lacey, but the reply he had received in all cases was that it wa impossible to give such figures since they varied so greatly betwee different cases. He was therefore limited to his own resources i the matter. He had approached colleagues in the electrical industr who had actually carried out such work, and contractors who ha actually put in the pipes on behalf of the gas industry, and by tha means he had ascertained the figures given for costs per mile. A no contradictory figures had been quoted he presumed that th figures given in the Paper were sufficiently accurate for the purpos for which they had been prepared.

It had been found to be totally impossible to obtain an general figures relating to the cost of electrical transformers an sub-stations, and they had no parallel in the gas industry. Th costs seemed to vary so widely, to have so little relation to the thermal output and to depend so much on other featur that it was even impossible to obtain a "middle" figure whic would give a representative idea of the cost per 100,000 B.Th.U distributed. An average figure would convey no information wha ever. It was therefore impossible to give a bibliography relating t those figures, as had been requested by Mr. Donkin. The cost equipping buildings with electrical cables and gas-pipes was obtaine from the Author's own experience of installing systems insid buildings.

Criticisms had also been directed against the accuracy of th representative costs of production of gas and electricity as given Table I of the Paper. Here again there was a very wide variatio between the recorded costs of various stations; an average take over a large number of stations would mean nothing, and wou not be any more valuable for the purpose of general informatio than correctly representative figures. The figures actually give were well within recorded limits in all cases.

It would be observed that in all cases the approximate costs we given as a single digit, for the express purpose of indicating the approximate character, as any decimal places would have presum a certain degree of accuracy. The figures for fuel-consumptio per unit were obtained by calculating the figure from what w believed to be the most efficient installation in the British Island namely the Portishead station of the Bristol Corporation, in whi

1 kilowatt-hour was delivered for a fuel-consumption of 1·15 pound. The Author. The cost of coal varied greatly, but a representative cost was taken as 12*s*. per ton; the fuel-cost per unit on that basis would be about 0·075*d*. That figure was then compared with the average of the total units recorded as having been generated in the United Kingdom, namely, about 13×10^9. The total coal burnt was about 10×10^6 tons, from which it appeared that a general average consumption was 1·74 pound per unit generated, the cost of which at the same rate was 0·118*d*. per unit. From those two figures he concluded that a reasonably representative figure giving a fair idea of the cost of coal would be 0·1*d*. per unit. That figure was slightly below the average but was well above the best.

The other items of cost had been determined in a similar manner, and he saw no reason to doubt that the figures given in Table I gave as good a general idea of the approximate cost of generation as could be collated. The figures given in the various Tables had been calculated from data and efficiencies given in the Tables themselves, so that their origin could not be in any doubt. Since the figures of efficiency which were given in the Tables had largely been calculated, it would be easy for anyone to alter them if he so desired.

The representative figures for efficiencies of single fittings and heaters had in many cases been determined from his own tests and observations on commercial apparatus obtained for that purpose. What he had called the practical figures of equivalents had been obtained either from installations put in by himself, or by the very convincing method of turning his own house into a form of laboratory; he had employed the latter method for many years, actually using the various appliances in practical service and recording daily readings of meters installed and connected up for the purpose of obtaining the necessary information. It was almost unnecessary to add that the records had been made without the remotest trace of bias in any direction. It was clear that such comparisons could only be made one at a time between two specific pieces of apparatus, and if either apparatus were changed for one more or less efficient the results might be slightly different in some cases. In his own house many different types of apparatus, of exactly the type that the public would buy, had been tried. The figures given were what he believed gave the most accurate information obtainable.

Mr. Masterman, who spoke as a technical representative of the gas industry, seemed to think that the Paper should have given the figures obtained in his own laboratory—presumably from the most efficient appliances on the market—in the case of gas, compared

The Author. with the worst results obtainable in the case of electricity. Suc partisan comparisons would have been entirely misleading in Paper prepared for general use. The results as given in the Pape were such as would have been obtained by any member of th public who bought the apparatus in the open market and used in the same way as it was used in the Author's house; in h opinion such results were far more reliable as a guide to the publ than any laboratory tests could possibly be, for they incorporate all the causes of incalculable variation in general practical servic to which attention was directed in the Paper.

The Author feared that Mr. Masterman could not be acquitted distorting the very careful wording of the Paper in the interests his own industry. He strongly deprecated such an attitude. M Masterman said, for instance, that "the Author stated that by th agency of electricity . . . 'pure heat-energy can be delivered throug flexible wires in any quantity. . . .'" He went on to say that th electrical engineer himself would be the first to contradict th claim. The Author would reply, in the first place, that Mr. Maste man had omitted reference to the following words—"The amou which can be supplied is rigidly limited by the capacity of th generating plant and cables"—which appeared in the next sectio headed "*Disadvantages of Electrically-Derived Heat.*" He would al reply that his statement as it stood could not be contradicte because in fact pure heat could be delivered in any quantity throug flexible wires, naturally assuming them to be of appropriate siz To elaborate that point Mr. Masterman continued, with an examp already quoted in the Paper itself, to illustrate his superfluo argument that the amount of electrical power which could deilvered through a given cable was limited by the size of the cabl

Mr. Masterman was equally unhappy in his assumption that t Author was unfamiliar with the fact that the pressure-pulse syste of control was, or had been, in existence in various large cities. Th fact was stated in the Paper, but without names. Before citing Berl he would have been wise to make enquiries about that installatio The system was rarely installed now because it was generally u reliable. It blew the water out of wet gas-meters, caused flickeri of jets, extinguished pilot-lights, and had other practical defects.

Again, Mr. Masterman charged the Author with "propoundi the theory that if the products of combustion exceeded 212° condensation could not take place." That appeared to be a d tortion of the wording of the Paper, "If the temperature is n reduced below 212° F. all the vapour passes away with the pr ducts. . . ." The latter was a perfectly accurate statement whi

could not be denied, and was not a "theory propounded by the Author." In the cases quoted by Mr. Masterman the layer of gas in close contact with a cold surface in a gas appliance was actually reduced below 212° F., and therefore deposited condensation on the cold surface. He would have thought that a partisan of gas interests would not have emphasized that fact, as it was one of the grave drawbacks of the use of gas for such purposes. The Author.

Mr. Masterman stated that in Table XIV a column was based on a radiant efficiency of 100 per cent. That was a misrepresentation of the purpose for which that column was inserted, namely, to enable the reader to see at a glance what the cost would be in the limit if all the energy could be delivered as radiation. Nobody should know better than Mr. Masterman that a radiant efficiency of even 98 per cent. could not under any circumstances be attained at any temperature whatever.

Another mis-statement was that the Paper suggested that the average life of a gas-mantle was 350 hours. No such statement or figure was either given or implied in any part of the Paper, the only reference to the subject being that "The rate of deterioration of a good gas-mantle is about one-third . . ." of that of an electric bulb; that was true, and was in the exact opposite sense to Mr. Masterman's statement. Again, his statement that the accumulation of fur in a gas-boiler installation did not interfere with its efficiency would be very satisfactory information for all boiler-engineers if it were true, which it clearly was not. The Author most strongly deprecated that kind of criticism, especially when it was combined with indefinite charges of general inaccuracy.

Mr. Lacey, in the interests of the gas industry, emphatically protested against the Author's statement that the use of gas gave rise, along with the heat, to the emission of products of combustion which were mainly of a deleterious character. The Paper said that the use of any agent other than electricity (including coal, oil, wood and charcoal, as well as gas) gave rise to products of combustion. He would be a bold man who denied that in the main those products of combustion were of a deleterious character if introduced into the air in a room. If not, what was the object of providing a chimney for a gas fire or a geyser, thus wasting half the heat? Just as dirt was matter in the wrong place, so products of combustion in breathing-air were matter in the wrong place. Water vapour itself was deleterious when it made the atmosphere too humid, as it generally did. The sulphur content was always deleterious to fittings, and to such articles as piano-strings. Even carbon dioxide, accompanied as it usually was by a fractional pro-

The Author. portion of carbon monoxide, would have to be considered as deleterious product of combustion.

Mr. Bernard complained that Table XVII was a theoretical Tab in which all the equivalents were calculated from assumed efficienci and prices, and that due credit was not given to electricity for i various advantages, which were not represented in the Table. Tl Table was clearly labelled " Cost of heat only." If, in spite of tl explanations given, it should be read in any other sense, the Auth surely could not be criticized for that.

The Author was unable to agree with Dr. Fishenden that tl point of view of initial coal-consumption provided a simple way comparing gas and electricity. That consideration, important as might be in the national interests, had surely nothing to do wi the consumer, from the point of view of whom the Paper was main written. The consumer was only concerned with the prices at whi he could buy gas and electricity respectively, which had little no relation with the cost of the necessary coal. The Author h endeavoured to explain clearly in the Paper the reasons wl elementary B.Th.U. calculations of the relative amounts of heat gas and electricity had a very small bearing on the cost to tl consumer. That fact was clearly much more in favour of electrici than of gas, and gas partisans were therefore apt to insist on tl thermal comparison rather than on the facts of use, which it h been the effort of the Paper to explain.

The very interesting questions of the distribution of heat whi she raised could not possibly be discussed in a Paper such as tl Author's, which had already had to be severely curtailed in ord to bring it within a reasonable compass.

Mr. Roger Smith had suggested that the statement was inaccura that heat originally propagated as radiation was carried up tl chimney. The reason for that was that heat originally propagat as radiation was absorbed by the surfaces on which it fell, and a coming in contact with surfaces so warmed carried away as co vection heat originally propagated as radiation, which was ultimate therefore carried up the chimney by the current of warm a The interesting question about the effect of those hot products warming the walls of the house, and other questions relating the desirability of various forms of heat, were beyond the scope the Paper.

The Author could assure Mr. Dolby that there was nothi magical about the laws of thermo-dynamics. The installation Bourne & Hollingsworth had been recently declared by the clier to have been entirely satisfactory to them, both from a technic

The Author. and an economical point of view, after 8 years of service. Mr. Dolby might be recommended to visit that store during very hot or very cold weather and to judge the matter for himself.

Lord Pentland's criticism was that the Author had not taken into his purview the probability of future alterations in the relative cost of the two agents, and had made no reference to the variable factors of diversity and load-factor. To deal in a prophetic manner with such intricate questions in so general a Paper would have extended it indefinitely.

Mr. Grierson, in his interesting contribution, complained that the Author had not taken as a representative figure the high value of the efficiency obtainable at Barking, but the Author thought that an exceptional value of that kind would be out of proportion in a general Paper. The question of the relative danger of the two agents in time of war had been dealt with by the Author in the original draft, but had had to be eliminated in the interests of brevity.

The efficiencies of the insulation on water-heaters were taken exactly as supplied from the laboratories of the largest makers of those appliances in the British Isles. Mr. Nobbs criticized some of the figures of heat-consumption for hot-water supply as being excessive, and characterized 50,000 B.Th.U. as wholly excessive. The figures were ostensibly given as being the maximum that any engineer need provide, the large figure of 50,000 B.Th.U. having been taken from a very careful measurement of the Author's personal use of heat in his own house. It might be admitted that it was one of his few extravagances.

Commander Fairthorne appeared to have misconceived the meaning of the expression "efficiency" as applied to a cooker. The efficiency had either to be taken from cold or in the steady states, the two having little relation to one another. The figures in Table XVII represented the efficiency from cold, as observed on an actual apparatus.

Mr. Humphreys realized the difficulty of comparing agents so different as gas and electricity in the case of room-heating when the very involved questions of ventilation were taken into account. The making of comparisons did necessarily involve some attempt to ensure that the same conditions were obtained in the two cases. The experimentally-equivalent values of 10*d*. and 1*d*. for a gas fire and an electrical heater were quite definite in the Author's mind; his own study was equipped both with gas and electrical power, and frequent changes were being made even at present between the two installations, while observations were continually being made.

The Author. No accurate measurements of the equality of the heat deliver could be made continuously, the quantities measured being th costs of gas and electricity respectively when they were used to gi reasonable comfort to different persons using the room. In referen to Mr. Verity's request for heat-balances, that was an extreme involved question, and nothing of the kind could be given within reasonable compass.

A GENERAL COMPARISON OF GAS AND ELECTRICITY FOR HEAT-PRODUCTION.

PLATE 1.

FIGS: 3.

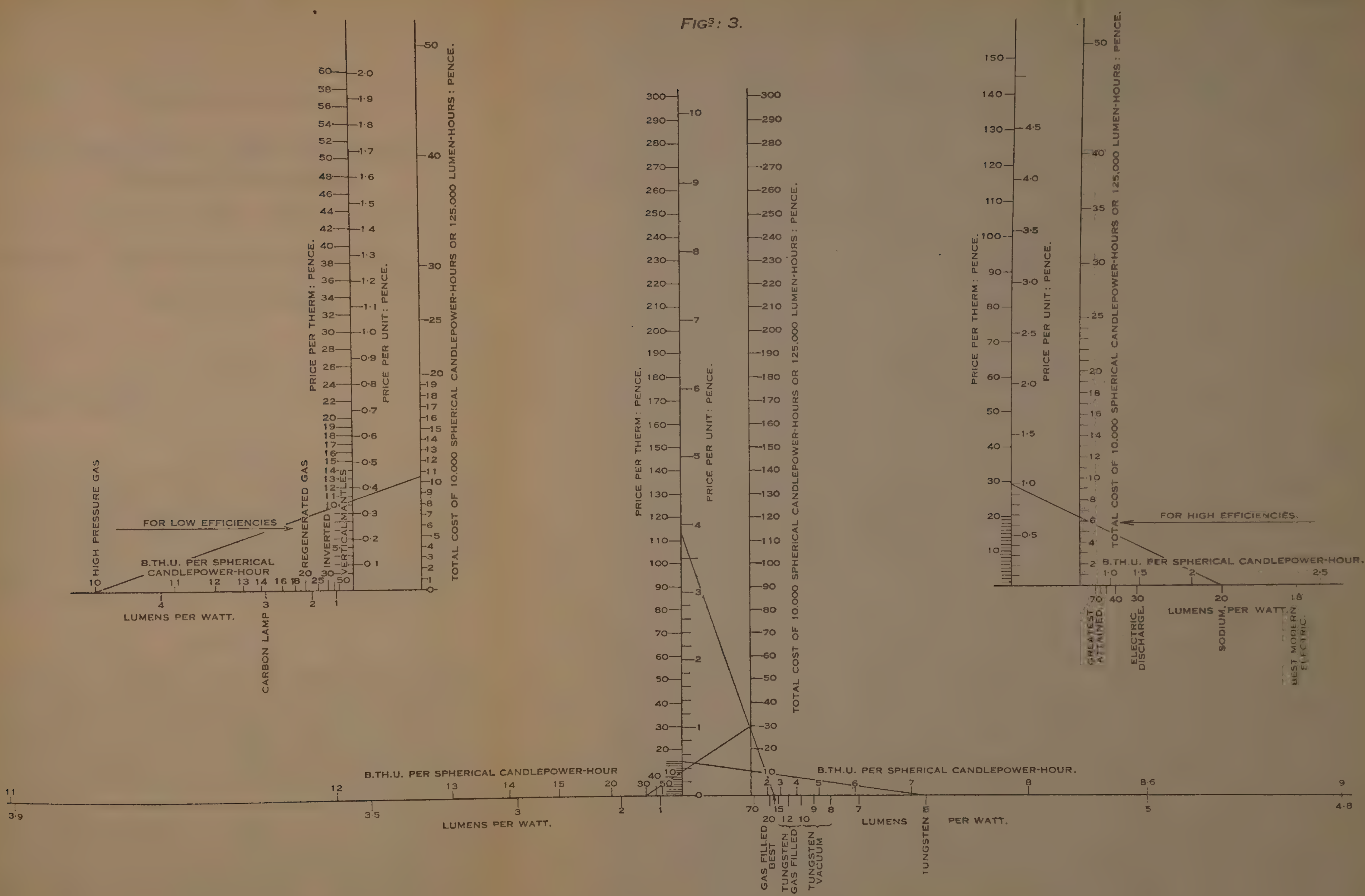


DIAGRAM FOR ESTIMATING COST OF LIGHTING BY ELECTRICITY AND GAS.

A. H. BARKER.

Student's Paper No. 926.

"The Construction of a Reinforced-Concrete Grain-Warehouse at Leith Docks."

By James Halliday, B.Sc., Assoc. M. Inst. C.E.

(*Ordered by the Council to be published without oral discussion.*)

TABLE OF CONTENTS.

SYNOPSIS.

The Paper describes the construction of the grain-warehouse on a foundation of piles, the main building, as well as a weigh-house, switch-house, and sack-store, being built entirely of reinforced concrete. The details given of the concrete work include descriptions of two Insley towers used for the hoisting of concrete. Special attention was paid to the shuttering to reduce unnecessary expense, although all the shuttering employed for the bins could not be used in repeat work. Information concerning the scaffolding, roof-covering, fire-precautions, and machinery and equipment installed completes the Paper.

Introduction.

The discharge and storage of grain at Leith Docks ranks to-day as one of the important sources of revenue of the port. The storage of grain by the Dock Commission originated in 1906. In that year a grain-warehouse, constructed of timber with an outer wall of brick, and having a capacity of 20,000 tons, was taken over from the private firm who had owned it. This warehouse was built in 1903.

In 1928 the storage-capacity was increased by the erection of a reinforced-concrete warehouse capable of storing 16,000 tons of grain. Both of these warehouses were situated at the extreme east end of the docks and were served by ship-discharging plant on the adjoining quays of the Edinburgh Dock. In 1930 the original timber warehouse was destroyed by fire, thus reducing the storage-

capacity to only 16,000 tons. The new grain warehouse at the Imperial Dock has been built to replace this older warehouse. The position of the various warehouses is shown in *Fig. 1.*

Fig. 1.

PLAN OF HARBOUR AND DOCKS.

The Imperial Dock is the largest dock at the port, and the depth of water over the sill is 4 feet 6 inches greater than that for the Edinburgh Dock, so that vessels of larger size and deeper draught

than could be accommodated at the older warehouse can be unloaded at the new site. Formerly, large vessels unloaded part of their cargo by tackle at the Imperial Dock before proceeding to the warehouse at the Edinburgh Dock.

The complete scheme for the new works included the following items:

(1) The construction of the warehouse itself, with a complete installation of grain-handling plant.
(2) The provision of two travelling pneumatic unloading-plants on the quay-side, with a conveying-gallery leading to the warehouse.
(3) The installation of two complete vacuum pumping-sets, each set consisting of two pumps with the necessary electric motors, starting-gear and equipment, in a pump-house inside the dock transit-shed.
(4) The construction of a sub-station with transformers and switchgear to supply power and light to the whole plant.
(5) The re-arrangement of railways and roads adjacent to the site and also the construction of several new railway lines and roads.

Item (5) was carried out by direct labour under the Commissioners' engineering staff.

The ground on which the warehouse is built has been reclaimed from the sea, and the bearing-value of the tipped material is rather doubtful. The depth of this material, which is immediately over the old sea-beach, is from 20 to 25 feet. A depth of approximately 40 feet must be obtained before a secure foundation can be assured in the boulder clay which is then encountered.

Piling.

Before piling was commenced, the site was thoroughly consolidated by means of a 15-ton roller. Whinstone bottoming, passing a 2-inch ring, was then laid down to form a 6-inch consolidated layer, the resulting surface being at the required uniform level.

The foundations for the building consist of nine hundred and seven reinforced-concrete piles, arranged in single lines under the longitudinal and transverse walls, and in groups of four or five under the columns. Diagrams showing the driving-resistance at various depths were drawn for a number of the piles, and showed the small resistance of the tipped material. An increase of resistance was shown when the old beach was reached. This, however, decreased when the beach had been penetrated and subsequently built up to

a safe value when the boulder clay was reached. At one part of the site an old sea wall was encountered; as the foundation of this old wall could not be depended upon, parts of it were excavated to allow piles to be driven to the level of the underlying boulder clay. The piles were formed in situ by means of the British Steel Piling Company's "Vibro" System, and had an average length of 40 feet, with a diameter of approximately 17 inches.

The materials used in the formation of concrete for the foundation-work were British Portland cement (complying with the relevant British Standards specification), washed pit sand, and whinstone from a local quarry. The concrete used to form the piles was a $1\frac{1}{2}$-to-2-to-4 mixture using $\frac{3}{4}$-inch stone, while for the floor-slab a 1-to-3-to-6 mixture was used with $1\frac{1}{2}$-inch stone. Pile reinforcement consisted of six mild-steel bars $1\frac{1}{8}$ inch in diameter within a 12-inch circle, with $\frac{1}{4}$-inch diameter spiral reinforcement.

Concreting.

On the completion of the piling work, a 6-inch thick floor-slab with a $1\frac{1}{2}$-inch layer of granolithic concrete was laid under the storage section of the warehouse. This floor-slab was increased to 12 inches in thickness under the conveyor tunnels and also where it formed wall footings. The ends of the pile reinforcement were allowed to project for a distance of 2 feet above the concrete surface, in order to give a secure bond with the walls of the warehouse.

In the front part of the building, which forms the delivery section, pits were formed to receive the lower ends or "boots" of the five grain-elevators which were afterwards installed. In the construction of these pits great care was taken to ensure an absolutely sound and watertight finish, this being necessary for the protection of the grain.

After the excavation for the pits was completed a concrete floor 21 inches deep was laid, pumps being employed to keep the work free from water. Walls 15 inches thick were then keyed into the floor. The pits were completely lined with "Pluvex" waterproof sheeting, on top of which an 18-inch floor and 24-inch walls were formed. A 1-to-2-to-1 concrete was used in the formation of the pits.

The new grain-warehouse is a rectangular building 159 feet long by 142 feet wide. It is built entirely of reinforced concrete and is divided into storage and delivery sections (Fig. 2, Plate 1). The storage section occupies four-fifths of the site and comprises sixty-nine silos, 12 feet 6 inches by 14 feet, and sixty silos, 14 feet by 6 feet 3 inches, all approximately 77 feet high, with reinforced-concrete

hopper-bottoms and pumice-concrete fillets. The larger bins each hold about 200 tons of grain, the capacity of the smaller ones being half that amount.

The front part of the building forms the delivery-section, which consists of an elevator-tower approximately one hundred and fifty feet above quay-level and a series of thirty delivery-silos. Seven floors are formed in the tower to hold the driving-gear for the elevators, the weighing machinery, and the conveying- and distributing-plant. Access to the various floors may be obtained by means of a passenger lift which extends from the ground floor to the top of the elevator-tower. A reinforced-concrete stairway is also provided and is built round the lift-well, while a cast-iron spiral stairway extends from the distributing floor to the top floor of the tower.

A weigh-house, a switch-house and a sack-store are attached to the main building, all three being built of reinforced concrete and constructed at the same time as the main building. The weigh-house contains the necessary machinery for weighing the incoming grain. Electric cables from the sub-station enter the building at the switch-house, and the main switches for all the motors in the building are installed at this point.

The railway-sidings which it was intended to use in connection with the grain traffic were laid down before construction was started, and provided excellent facilities for the delivery of materials and equipment to the site. The contractors were required, by a clause in the conditions of contract, to fence in that part of the ground surrounding the site which was considered necessary for the execution of the works. The contractors were encouraged to use as little space as possible by being charged a nominal rental for the ground occupied; this ground, adjoining the quays and wharves, was required for depositing ships' cargoes, and no interference with the general traffic of the port was allowed.

When the concrete work forming the roof of the storage-section was reached the carpenters' benches were removed from a site on the east side of the warehouse to the distributing-floor, and were afterwards moved to the various floors of the tower as the work progressed. The hoisting of heavy shutters was thus avoided as far as possible.

The reinforcing rods were shaped and stored on an area to the west of the warehouse, and a railway-siding running across the site enabled materials to be delivered directly to this area. Two electrically-driven bending machines were installed capable of dealing with the maximum diameter of reinforcement used. The bent steel was hoisted to the required level by means of an electric

winch which was placed at the north-west corner of the building. A cathead was formed by the timber scaffolding at this point to give sufficient headroom for the lift.

One of the major considerations in constructions of this type is the hoisting of materials to the required level. The hoisting of concrete was performed by two Insley towers. The larger mast was 250 feet high and approximately 4 feet 9 inches by 7 feet in cross-section. It was placed in the front line of storage-bins and positioned so as to clear the bin walls. Owing to the presence of the mast, the hopper-bottom of one storage-bin had to be omitted, and this was constructed after the removal of the Insley tower. A section of the distributing-floor, pent-house floor and pent-house roof had also to be left out in the first instance. In all these cases the usual reinforcement was placed to bond with the rest of the work, and it was then bent aside where required in order to clear the tower, and secured until the tower was dismantled. A check was also formed in the concrete surrounding the openings to ensure a good joint when fresh concrete was deposited against the old material.

The position of the mast was chosen to give the maximum control possible over the work. Anchor-bolts were sunk and grouted into the concrete floor to hold the base, while guys were attached to the mast at every 20 feet. To ensure that these guys did not pass through any vital part of the structure, oblique sections of the building were drawn on the proposed line of the guys. The anchorages were then, if necessary, moved slightly until the guy cleared all columns, beams and castings.

A bucket running on guides inside the mast formed the means of hoisting the concrete, an electric winch placed about 40 yards outside the building supplying the necessary power. The hoisting-rope running from the winch to the mast passed through the wall footings and had to be boxed, the holes so formed being afterwards filled. The hoisting bucket, on reaching a predetermined level, automatically tipped its contents into a steel hopper, the discharge from which was controlled by hand. A jib attached to the mast, and capable of slewing through 180 degrees, supported a truss which could be turned through a complete circle. Shoots were led from the steel hopper at the mast to the end of the jib-tackle and thence down the rafter of the truss. By this means concrete could be supplied to the larger part of the work, a strip along the back wall being the only part of the building which could not be supplied from this mast. The jib, truss and steel shoots formed one complete unit, which could be moved up or down the mast to any required height.

A smaller Insley mast, 100 feet in height, was erected at the

north-east corner of the building. Concrete was raised in a steel hopper, running on guides fixed to the side of the mast; the hopper discharged automatically into a receiving-hopper which was kept at the level at which the work was proceeding. Barrows were used to distribute the concrete and were filled from the hopper by a hand-operated valve. Motive power for hoisting the hopper was supplied by a petrol-driven winch placed beside the main building.

A concrete-mixer with a capacity of $\frac{3}{4}$ cubic yard was used to supply the large mast. Its position at the base of the mast was immediately over the elevator-pits which run across the building between transverse walls Nos. 11 and 12. These five pits were temporarily boarded over with 9-inch by 3-inch timber, the staging thus formed on either side of the mixer being used for the storage of sand and stone. The mixer discharged concrete into a shoot which ran through a convenient doorway in transverse wall No. 11 to the hoisting bucket. A railway-siding running through the building at this point was used for the delivery of the sand and stone, while cement was delivered at the dock by steamer and stored in a shed provided for the purpose.

At the east side of the building a railway-siding running within a few yards of the small mast was connected up to the main line, and thus enabled materials to be dumped conveniently close to the mixer. A second cement-shed of smaller capacity was constructed to serve this mixer, and a water-connection to the main dock-supply ensured an adequate supply of clean, fresh water.

For all reinforced-concrete work in the warehouse a 1-to-2-to-4 mix was employed, but for unreinforced ground-floor work a 1-to-3-to-6 mix was used, the concrete being laid on a 6-inch layer of stone bottoming. A wearing surface consisting of a 1-inch layer of granolithic concrete was laid over all floors and stairs, a $1\frac{1}{2}$-inch layer being laid over the fillets forming the hopper-bottom of the bins. These fillets were formed of pumice, as no great strength was required and the saving in weight so effected was quite considerable. The wearing surface was required to withstand the action of the grain.

British Portland cement was used throughout the building, each consignment being thoroughly tested on behalf of the Dock Commissioners before dispatch from the works. Examples taken from a typical series of tests gave the following results:—

Mean strength of six briquettes at end of 3 days = 592 pounds.
Mean strength of six briquettes at end of 7 days = 597 pounds.
Percentage left on a sieve of 5,184 meshes per square inch = 0·17.
Percentage left on a sieve of 28,900 meshes per square inch = 3·85.
Initial set = 3 hours 5 minutes.
Final set = 4 hours 25 minutes.

The washed sand was graded in the following proportions :—

All the sand had to pass through a $\frac{3}{16}$-inch mesh.

30 per cent. of the whole was retained on a sieve of 900 meshes per square inch.

70 per cent. of the whole was retained on a sieve of 2,500 meshes per square inch.

Sand intended for use in mortar was passed through a sieve having 400 meshes per square inch, and was entirely free from any trace of salt.

The stone used for forming the concrete was whin, obtained from a local quarry. For reinforced work the stone was made to pass a $\frac{3}{4}$-inch ring and was graded down to $\frac{1}{4}$ inch. Tests carried out on stone from this quarry gave a crushing load of approximately 1,000 tons per square foot.

Tests made on 6-inch cubes of concrete as deposited on the work gave the following results :—

Mean strength of two cubes at end of 1 month = 2,218 pounds per square inch.

Mean strength of two cubes at end of 3 months = 3,683 pounds per square inch.

Mean strength of two cubes at end of 1 year = 3,976 pounds per square inch.

Shuttering and Scaffolding.

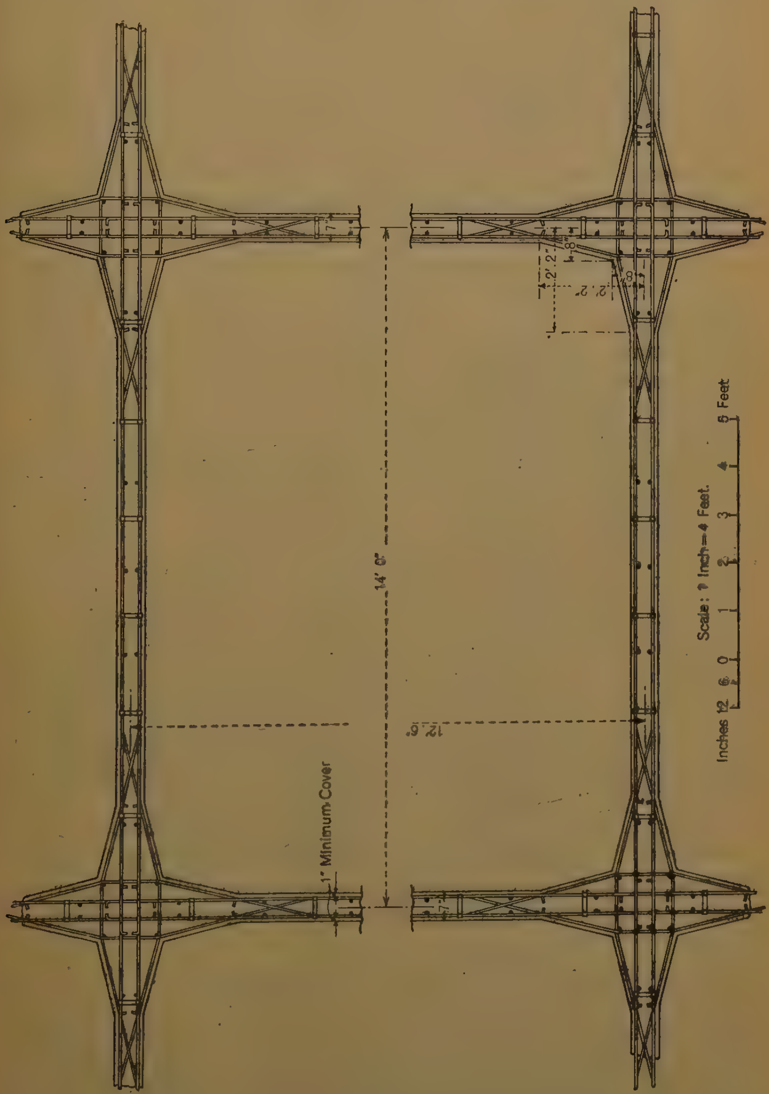
Shuttering.—In a reinforced-concrete building of this type, the cost of shuttering forms a very substantial part of the total contract. Great care was taken, therefore, to design the various shutters in order to ensure that they were capable of being used as many times as possible. That part of the warehouse below the distributing floor lent itself exceptionally well to this treatment. The storage-bins are formed by a series of longitudinal walls at 14-foot centres, intersected by a series of transverse walls at 12-foot 6-inch centres. The wall-junctions are splayed to form piers. A complete plan of a storage-bin is shown in *Fig. 3*.

A clause in the specification relative to shuttering required timber of good quality and of a minimum thickness of 2 inches, with all joints tongued and grooved. The use of 2-inch timber ensured a good straight wall and also allowed shutters to be cleaned up several times before their strength was seriously affected.

Two shuttering-units were used to form the bins, namely vertical casing for the splayed corners and plain sheeting for the straight walls. The corner casing was at first made in 6-foot lengths, but as the work progressed this was found to be somewhat unwieldy

and a 3-foot length was adopted. The plain sheeting was built into shutters using 4-inch by 2-inch cleats and was made to fit loosely between the vertical casing. Timber breaking-out pieces 2 inches

Fig. 3.



SECTIONAL PLAN OF STORAGE-BIN.

by 1 inch were then inserted in order that the shutters could be stripped without damage to the surface of the concrete. A lift of shuttering was approximately 3 feet. Two 6-inch by 3-inch walings

were used per shutter, one in the centre and another one at the top overlapping by $1\frac{1}{2}$ inch, so that it also supported the next shutter. The shuttering was held together by $\frac{5}{8}$-inch bolts, which were encased in four-ply cardboard tubes wherever they passed through the walls. When the shuttering was stripped, these tubes were driven out and the holes filled with cement-mortar. The corner piers of the outside walls were accurately plumbed from ground-level as each lift of shuttering was placed, the vertical shutters in this case being 6 feet long. A heavy weight suspended by a wire was used for plumbing, and after setting the corner shutters, wires were stretched from corner to corner and the remainder of the shutters were then placed in line. The position of the shuttering for internal walls was fixed by means of wires extending between the outside walls. The accuracy of this method is shown by the fact that on testing the corner piers after completion of the building, the maximum error out of plumb did not exceed $\frac{3}{8}$-inch. Two complete sets of shuttering were constructed for each bin, these being used in "leap-frog" fashion as the work progressed. Details of the shuttering used to form the storage-bins are given in *Figs. 4.*

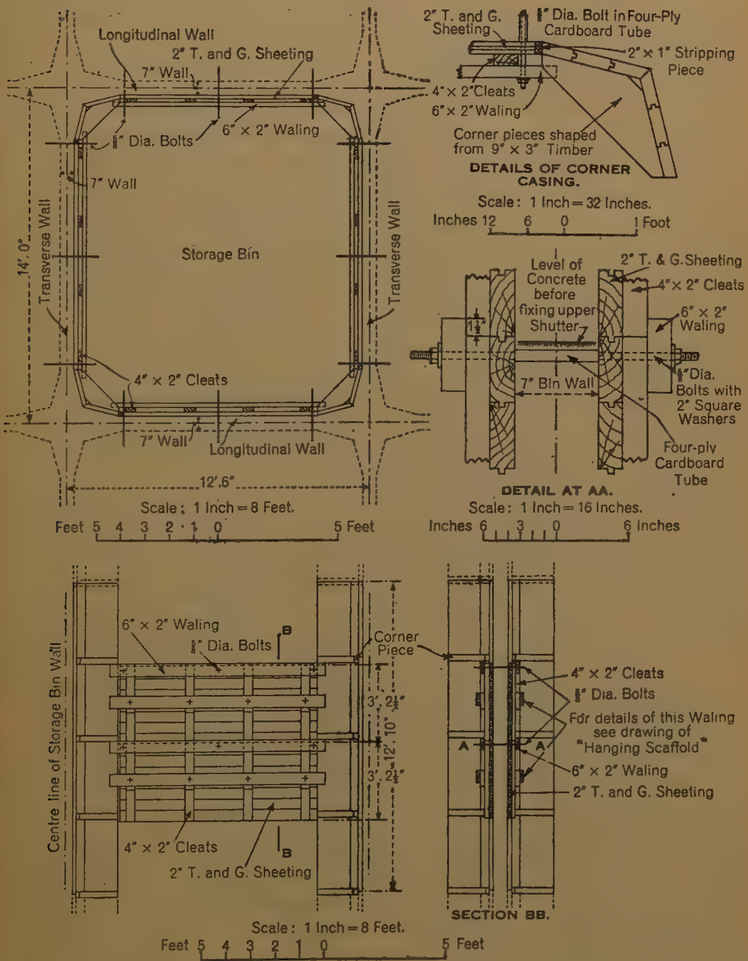
A more difficult problem was encountered in the design of centering to form the inclined slabs of the bottoms of the bins. In this case, two supporting beams had to be incorporated in the scheme. A 9-inch by 3-inch timber running parallel to the bottom of the bin formed the main support. It was fixed in position by means of two 6-inch by 2-inch struts, and was bolted at its upper end to the corresponding frame in an adjacent bin. The complete framework was rested on the horizontal walings of the wall shutters below. Folding wedges were inserted so that adjustment to the proper lines and levels could be carried out subsequently. The remainder of the shuttering was built up on these frames. The shuttering of the bottom of the bin is shown in *Figs. 5* (p. 314).

The inclination of the slabs forming the bottoms of the bins being 45 degrees, top shuttering was required. A V-shaped shutter was used to form the bottom angle, and this was held in its correct position, relative to the bottom shutter, by means of timber spacing-blocks.

Throughout the construction it was arranged that the joints between the slabs should be situated at mid-span; in the formation of the slab forming the bin-bottom, this meant that the top sheeting had to be carried well above the level of the beam-mould. To ensure that the concrete round the reinforcement of the beam was thoroughly tamped, three boards were left out at this point. They were placed in position immediately after the concrete for the beam was poured, the remainder of the slab being then filled up. A 12-

inch by 12-inch cast-iron draw-off grain-spout is situated in the bottom of each bin. These were fixed securely in position by means of 12-inch by 12-inch timbers over which the castings were fitted.

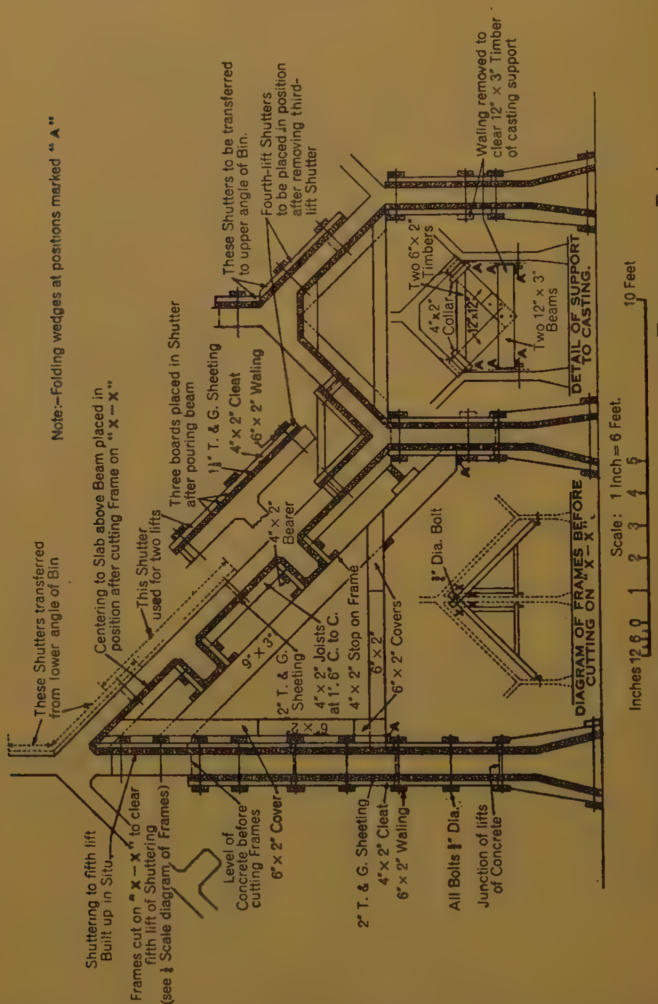
Figs. 4.



Practically all the shuttering for the bottom of the bins was actually built up in situ and could not be used in repeat work, but the timber, after being stripped and properly cleaned, was used again in the construction of other units of shuttering. This part of the work was probably the most expensive part of the shuttering. The maximum speed for shuttering was a height of 20 feet in 1 month.

The depth of the completed bins is about 77 feet, and to guard against accidents, a safety scaffold was provided in each bin. This consisted of a platform built up of 7-inch by 2½-inch bearers with 9-inch by 1½-inch decking which fitted loosely in the bin. It was

Figs. 5.



FRAMES AND SHEETING TO BOTTOM OF BIN (THREE FRAMES PER BIN).

suspended a few feet below the shuttering by four ropes from the horizontal walings of the shuttering, and was raised as the work proceeded. A trap-door was provided to give access to the bottom of the bin. The scaffold gave a feeling of security to the workmen engaged in the construction and enabled them to work more

efficiently than they otherwise would have done; it also proved useful in cleaning off the walls of the bin and in filling up bolt-holes.

When the distributing-floor was reached, boxes were left in the floor at each corner of the bin. The four supporting-ropes of the hanging scaffold were led through these holes and the weight was then taken off the shuttering. The scaffold was then used to strip the shuttering of the underside of the floor and also to remove the last of the wall shutters. The scaffold itself was dismantled as it hung, the last parts of this work being done from a boatswain's chair.

The construction for a typical floor was as follows. Boxing for the columns and walls was first brought up to the underside of the floor, lateral support being given by means of the soffits of the longitudinal and transverse floor-beams. The columns were then concreted to about 3 inches below the haunches of the beam, and the sides of the beam were then placed in position. Horizontal bearers were fixed to the sides of the beam in order to support the floor-joists, which were 4 inches by 2 inches placed at about 18-inch centres, and the decking was then placed over the joists. Before concreting was carried out, the floor was thoroughly propped, folding wedges being used to enable any adjustment to be carried out.

Throughout the building all re-entrant angles on the concrete were chamfered to form splay fillets, while the corners of all columns and beams were also chamfered. Beam soffits were cambered in the proportion of 1/300 to 1/360 of the span. Shuttering for the beams was arranged so that the side-members could be stripped without interfering with the rest of the shuttering. This enabled shuttering to be stripped in the following rotation:

Vertical-wall shutters, sides of beams and columns .	4 days.
Floor slabs	6 to 10 days, according to span.
Beam soffits	14 days.

Wash-out holes were left in all column-boxes to ensure that all sawdust, shavings and other foreign materials should be cleaned out before any fresh concrete was deposited.

Scaffolding.—In accordance with the provisions of the specification an efficient and complete scaffold was erected around the building. The framework was constructed of timber poles with wire lashings, the runways, placed at 6-foot vertical intervals, being built up with 4-inch by 4-inch hardwood joists and 9-inch by $1\frac{1}{2}$-inch decking. Handrails and kicking-boards were also provided. Access to the scaffolding was obtained by means of a runway at the north side of the building. Ties, made of steel wire $\frac{1}{4}$ inch in diameter, were fixed to the building through constructional bolt-holes, and gave

lateral support to the scaffold. The scaffold was continued to the highest point of the tower and provided an excellent means of inspecting the work.

Reinforcement.—Steel for reinforcement consisted of plain mild-steel bars. It was specified to comply with the British Standard Specification for Structural Steel for Bridges and General Building Construction. Tests of each consignment of steel delivered were carried out by the engineer at the manufacturer's works.

The main reinforcement in the wall was placed horizontally and was bound securely to the vertical distributing-bars by means of pliable iron wire. Each pair of horizontal rods was accurately spaced according to the thickness of the wall, ½-inch by $\frac{1}{16}$-inch-thick steel clips being used for this purpose. The heavy reinforcement of the beams was supported on pre-cast concrete blocks to ensure proper alignment. The usual reinforcement for the columns consisted of $1\frac{1}{8}$-inch diameter verticals with ¼-inch binding and links. To prevent damage to the corners of columns by barrows, column guards, consisting of angles and flats welded together into a framework, were embedded in the concrete at the base of each column for a height of 4 feet 2 inches.

Final Details and Equipment.

Roof-Covering.—All the flat concrete roofs were waterproofed in the following manner. The entire surface of the roof, having been finished with a smooth surface, was covered with a layer of "Stoneflex" felt. On top of this was laid a ½-inch layer of pure mastic asphalte. A finishing coat was then applied consisting of a 1-inch layer of asphalte mixed with 20 per cent. by weight of ¼-inch granite chips. The various layers were arranged so that all joints overlapped. The asphalte was continued up the parapet walls which surround each roof in order to form a 6-inch upstand, this being finished off in a raggle let into the concrete. Gutters were formed in the asphalte along the external walls and drain all the water from the roofs into down-pipes, which were installed at frequent intervals.

Asphalte boilers were placed at the east side of the building, and were able to supply material for practically all the roof areas. The small Insley mast was used as a hoist, a platform being constructed inside the concrete-hopper in order to take buckets of asphalte. The roof over the main storage section of the building was laid in this manner, but for the roof of the tower a timber cathead was constructed, projecting over the parapet wall. The hoisting-rope

from the large Insley mast was then led from the winch to this cat-head and was used to raise a timber platform on which the asphalte buckets were placed.

Verandah.—To enable grain to be delivered from the warehouse during unfavourable weather-conditions, a verandah was constructed along the south side of the building. It consists of steel cantilever trusses at 9-feet 4-inch centres, securely anchored to the building by means of 3-inch by 1-inch rolled-steel flats. These ties are continued back through the walls of the delivery-bins and are anchored in the columns of transverse wall No. 12. The covering for the verandah-roof consists of corrugated asbestos-cement sheeting. Adequate roof-lights are provided, glazed with $\frac{1}{4}$-inch rough-cast wired glass.

A service-pipe with a connection to the dock water-mains is installed in the building to provide a supply of water in case of fire. It extends from the ground floor to the fourth floor of the tower and is provided with nozzles and hoses at convenient points on the various floors. A fire-escape extending from the roof of the storage section to the ground is provided on the west wall of the warehouse. From the storage-roof a steel ladder leads to the pent-house roof and from there a fire-escape extends up the north wall to the fourth floor of the tower. The fire-escapes throughout are constructed of steel sections and are provided with chequer-plate landings and steel handrails. Swing doors built up of steel plates and fitting into steel door-frames are provided at the various floor-levels.

At the conclusion of the work, the entire outside surface of the concrete was given two coats of neat cement. This was applied with brushes, care being taken to ensure a uniform finish. Inside the building the surface of the concrete was given two coats of "Snowcrete" cement.

Equipment.—The ship-discharging plant which feeds the warehouse is of the pneumatic type. It is installed on the quay at No. 6 Shed, Imperial Dock, and consists of two unloading towers, which are equipped with electric motors enabling them to take up any desired positions on the quay. Two sets of grain suction-pipes are suspended from each structure, and these are provided with regulating nozzles at their lower ends. When the plant is in operation, the nozzles are partially buried in the grain in the ship's hold. An air-inlet regulator-valve is situated at the top end of the nozzle and can be adjusted to suit the feed of grain. The grain drawn into the nozzle is carried up the pipe-lines by the velocity of the air into a large receiving chamber, where, owing to the drop in the velocity of the air, the grain falls to the bottom of the chamber. It is then discharged by means of a mechanically-operated air-lock

discharger into the boot of a bucket-elevator. The grain is then raised by the bucket-elevator to the top of the structure, whence it is passed down a steel shoot to the conveyor-belts in the gantry. The gantry is a steel-framed structure running above the roof of No. 6 Shed and from there across to the warehouse, and is supported on trestles throughout. It houses two conveyor-belts, each of which is capable of carrying the specified capacity of each unloading plant, namely 180 tons of wheat per hour.

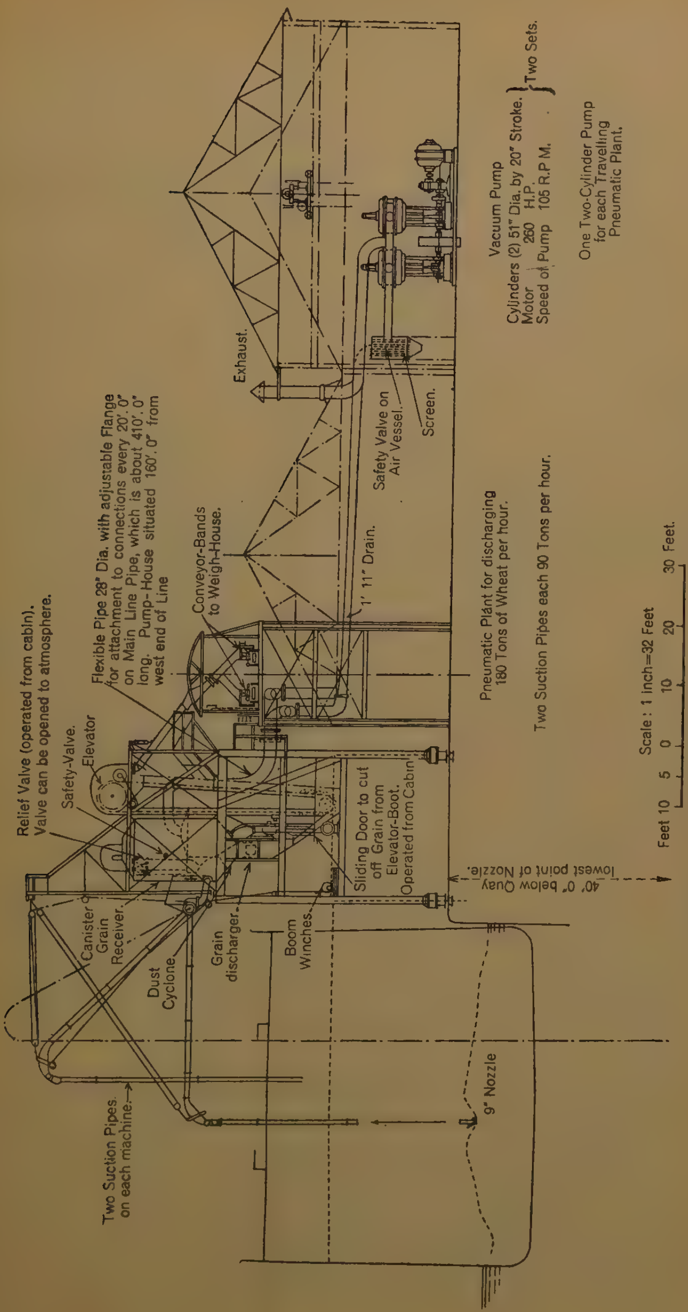
The vacuum in the system is created by two sets of pumps situated in a pump-house in No. 6 Shed. These pumps are of the vertical double-acting type, and are capable of maintaining a steady vacuum of about 10 inches when working under normal loading. Each set of pumps is driven by an electric motor of 260 HP. Air-intake pipes are led from the pump-house to the front of the shed and along the front of the conveying-gantry, and T-pieces have been inserted at 30-foot intervals, to which the elevator-towers can be connected. Power supply to the towers is by means of a system of electric conductor-rails fitted along the front of the gantry.

When the grain is removed from the receiver by means of the automatic discharger, the air and dust are carried on through a system of cyclones and pipes to the pumps from which the purified air is exhausted into the atmosphere. While the air is passing through the cyclones, the particles of dust are extracted and fall to the bottom of the container, from which the dust is drawn off in bags. A cross section through the grain-discharging plant is shown in *Fig. 6*.

After being discharged from the unloading plant the grain is conveyed along the gantry to the warehouse, which it enters through the weigh-house. The weigh-house is equipped with two 2-ton automatic weighing machines with receiving and delivering hoppers. All grain entering the warehouse must pass through these weighers, each of which can weigh continuously at the rate of 180 tons of wheat per hour. Grain is drawn from the delivery-hoppers through steel shoots to either of the two main intake conveyor-bands. These run at different levels transversely across the main building, and are equipped with throw-off gear which enables grain to be shot into any of the five elevator-boots. The conveyors travel at 700 feet per minute and can each take 360 tons of wheat per hour. A longitudinal section of the warehouse is shown in Fig. 7, Plate 1.

The warehouse is designed so that it can operate in five distinct sections, each of which is complete in itself but is connected by shoots with the sections on either side. Three of the bucket elevators can raise 360 tons of wheat per hour, while the other two can each deal with 180 tons per hour. The elevator-legs are enclosed in steel

Fig. 6.



Section through Pneumatic Grain-Discharging Plant.

casings. The driving mechanisms are situated on the fourth floor of the tower, and each consists of an electric motor driving the top elevator-pulley through 20-to-1 double-helical reduction-gearing.

From the elevator-head grain can be sent either to the storage or the delivery sections. The elevator-head is connected directly by shoots to the first four lines of storage-bins, so that, if required, the grain can be fed into these bins by gravity. The remainder of the storage-bins are fed from the conveyor-belts on the distributing-floor. Laying-on hoppers are used to regulate the flow of grain from the elevator-head to the conveyor-belt, and portable throw-off gear, which can be placed anywhere in the length of the belt, discharges the grain into the selected storage-bins. The capacity of the conveyors is 360 tons per hour, while the bins can hold approximately 200 tons.

Grain to be delivered from the warehouse is drawn off from the storage-bins by means of valves and spouts, and is run on to conveyors which are placed in the tunnels under the bins. Five of these conveyors are provided, each of which can carry 180 tons per hour. They discharge grain again into the elevator-boots, and from there it is raised to the elevator-heads and discharged into the delivery-shoots. Five 3-ton automatic weighing-machines are installed on the second tower-floor and are each provided with receiving and delivery hoppers. Grain leaving the warehouse is usually weighed and then passed by means of a revolving shoot to the required delivery-bin. From the delivery-bins the grain can be discharged in bulk or it can be weighed by portable automatic sack-weighers, the sacks being then passed down timber sack-shoots to the waiting lorry.

An electrically-operated temperature-indicating apparatus is installed to read the grain-temperature in the storage-bins at intervals of 10 feet of depth, a switchboard being provided at the north side of the distributing-floor. The reading of grain-temperatures is part of the daily routine-work of the warehouse, as it is an indication of the condition of the grain. A cross conveying belt is provided on the distributing-floor for changing grain from one delivery-bin to another.

Grain as delivered from vessels usually contains quite a large amount of dust. To deal with this two dust-extraction plants are installed on the third floor of the tower. Each plant consists of an electrically-driven fan which creates a vacuum in a system of pipes distributed throughout the building. These pipe-mains can be coupled up to all points of grain-discharge by means of flexible piping. Suction-points for floor-sweeping are also provided. Dust is collected from the system on the second floor of the tower, and i

conveyed in bags to the delivery-floor by means of a spiral shoot provided for the purpose. Exhaust air from the system is delivered to the atmosphere through cowls situated on the roof of the tower. Before being exhausted into the atmosphere, the air is passed through a cyclone, where a large proportion of the heavier dust is retained. The lighter dust is carried on with the air and is exhausted into a settling chamber, from which the clean air is delivered to the atmosphere. A similar plant is installed in the weigh-house.

A 30-cwt. passenger lift of the push-button-control type is installed in the south-west corner of the storage section. The elevator-well runs from ground-level to the fourth floor of the tower and is 5 feet by 5 feet with $4\frac{1}{2}$-inch thick walls. Collapsible iron gates are provided at each of the eight landings leading to the various machinery-floors. A reinforced-concrete stairway has been constructed around the elevator-well running from ground-level to the level of the tower-roof. The complete scheme is shown in Figs. 8, Plate 1.

Work on the warehouse commenced in July, 1932, and the roof of the room containing the lift-motor, which was the last piece of concrete to be formed, was deposited in November, 1933. The building was officially opened on the 28th May, 1934, and the installation of the machinery and equipment was completed after that date.

The Paper is accompanied by thirteen sheets of drawings, from some of which Plate 1 and the Figures in the text have been prepared, and by sixteen photographs.

The Council invite written communications on the foregoing Paper, which should be submitted not later than three months after the date of publication. Provided that there is a satisfactory response to this invitation it is proposed, in due course, to consider the question of publishing such communications, together with the Author's reply.

Paper No. 5033.

"The Stability of the Compression-Flanges of Through-Bridge Plate-Girders."

By ALBERT NOEL PROCTER, M.Sc. (Eng.), Assoc. M. Inst. C.E.

(Ordered by the Council to be published without oral discussion.)

TABLE OF CONTENTS.

SYNOPSIS.

The Paper deals with the stability of the compression-flanges of through-bridge plate-girders. The stability is affected by the rigidity of the end-posts, by the wave-length of the compression-flange, and by what is termed the "loading-coefficient"; the latter is dependent on the type of loading. The effects of stiffeners, flange-plate curtailment, form of the compression-flange, and secondary stresses are considered, and the safe working-stress is indicated. Reference is made to possible sources of error in the formulas, and two numerical examples are included. The Paper concludes with a summary of the most important points which arise in the design of through-bridge plate-girders.

INTRODUCTION.

THE design of structures is generally carried out by one of two methods. The first is the direct method, by which the size and proportions of a member may be deduced directly by calculation, as in the case of ties and beams, and the second is the indirect method, which may be described as "trial and error," where the size of the member has to be assumed before the calculations can be made. Arches and struts fall into the latter category, as well as laterally-unsupported beams and compression-flanges of through-bridge girders. The existence of the two methods is due to the dual nature of the conditions of stability of structures. Generally the strength of a member or structure is limited by the direct strength of the material, but under certain conditions it may be dependent on its elastic stability. The first condition may be calculated directly,

but the second is dependent on the form of the member or structure and also on the restraint imposed upon it by adjacent members.

The design of the compression-flanges of through-bridge girders involves a combination of the two methods, because failure may occur either by direct compression or by lateral buckling; hence, although the flange proposed may be adequate to resist direct forces, a check-calculation should be made to test the conditions of elastic stability. This Paper deals only with the stability of through-bridge compression-flanges, it being assumed in all cases that the specified working-stresses in direct compression are not exceeded.

A through-bridge plate-girder is usually of such depth that overhead bracing of the compression-flanges would seriously restrict the headroom over the deck. The girder itself must therefore be made sufficiently stiff to resist lateral buckling. It is usual to neglect the support which the stiffeners afford, and to design the compression-flange to resist unaided all lateral forces applied to it, either externally or internally. The details of the connections between the deck-beams and the main girders have considerable influence on the stability of the compression-flange, for the following reason. The steelwork of the deck is generally composed of fairly deep cross-beams, which are often embedded in concrete, so that the stiffness of the deck is considerably greater than the lateral stiffness of the main girder. If the connection between the cross girders and the web of the main girder is rigid, the lower part of the main girder is fixed in direction and position. The formulas which follow in this Paper have been based on the assumption that the connections between the cross girders and the main girder are reasonably rigid. It has also been assumed that the girder behaves as a homogeneous member and obeys Hooke's law.

The end-stiffeners of the girder are usually of heavy construction and are usually rigidly attached to the bearings. The reaction of the bridge on the bearings will in most cases tend to hold the end-stiffeners upright, and so fix the position of the ends of the compression-flanges. The fixity of the end-stiffeners may, however, be only partial. This condition will be considered later.

In order to obtain a general formula, it is proposed to investigate the case of a plate-girder having rigid end-stiffeners, and having the bottom of the web fixed in direction by the connection of the deck-steelwork. The girder is also assumed to have a uniform bending moment along its entire length (as explained in Appendix I, p. 342), no intermediate stiffeners and no flange-plate curtailment, and to have all loads concentric and vertical. The adjustments for any of the above variables may be made by suitable substitutions in the general formula.

LIST OF SYMBOLS.

NOTE: Except as otherwise stated all lengths are in inches and all forces are in tons.

Let A denote the gross area of the compression-flange.
,, b ,, ,, breadth of the compression-flange.
,, d ,, ,, overall depth of the girder.
,, d_c ,, ,, spacing of the cross girders.
,, d_s ,, ,, spacing of the stiffeners.
,, E ,, ,, Young's modulus.
,, f ,, ,, main bending stress in the compression-flange.
,, f_b ,, ,, stress in the compression-flange due to lateral bending.
,, f_c & f_w ,, ,, buckling stress of the compression-flange.
,, GJ ,, ,, torsional stiffness of the girder.
,, h ,, ,, depth of the web to the centre of the cross girders.
,, I_c ,, ,, moment of inertia of the cross girders.
,, I_F ,, ,, moment of inertia of the compression-flange, about an axis in the plane of the web.
,, I_s ,, ,, moment of inertia of a pair of stiffeners, about an axis in the plane of the web.
,, i ,, ,, inclination of the ends of the cross girders.
,, K ,, ,, loading-coefficient (Table I).
,, K_w ,, ,, loading-coefficient (Table II).
,, L ,, ,, length of the compression-flange.
,, L_c ,, ,, length of the cross girders.
,, L_w ,, ,, wave-length of the compression-flange.
,, M ,, ,, the applied bending moment in tons–feet.
,, m ,, ,, flange-plate curtailment-coefficient (Table III).
,, n ,, ,, ratio of L/L_w.
,, P ,, ,, total thrust in the compression-flange.
,, P_w ,, ,, total normal wind-load on the side of the girder.
,, p ,, ,, intensity of wind-force on the side of the girder.
,, R_F ,, ,, the resilience of the bent compression-flange.
,, R_J ,, ,, the resilience of the twisted girder.
,, R_s ,, ,, the resilience of the bent stiffeners.
,, R_w ,, ,, the resilience of the bent web.
,, T ,, ,, torque applied to the girder.
,, t ,, ,, thickness of the web.
,, W ,, ,, total live load on the deck.
,, W_k ,, ,, the work done by the compressive force on the buckled flange.
,, W_J ,, ,, the work done in torsion on the girder.
,, y & y_0 ,, ,, lateral deflection of the compression-flange.
,, z ,, ,, lateral deflection of the stiffeners.
,, θ ,, ,, angular displacement of the main girder.
,, σ ,, ,, Poisson's ratio.

GENERAL CONDITIONS OF STABILITY.

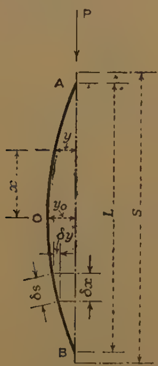
The girder represented diagrammatically in *Figs. 1* and *2* will first be considered. The full line AOB (*Fig. 1*) represents the plan of the centre line of the compression-flange at the instant of failure.

The principal dimensions are as follows :—

L, the length of the compression-flange.
A, the area of the compression-flange.
I_F, the moment of inertia of the compression-flange about an axis in the plane of the web.
h, the depth of the web measured from the centre of the compression-flange to the centre of the cross girders.
t, the thickness of the web.

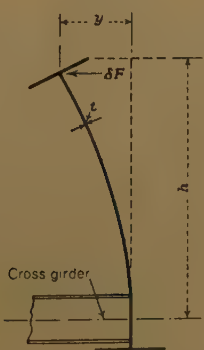
It will be seen that any deflection of the compression-flange

Fig. 1.



relative to the tension-flange (*Fig. 2*) must be accompanied by bending of the web. The amount of restraint exerted by the web on the compression-flange depends on their relative stiffnesses. A

Fig. 2.



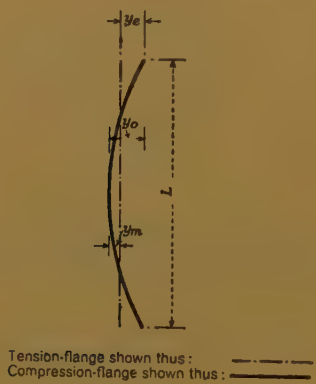
broad heavy flange will receive but little lateral support from a deep thin web, but a light slender flange will receive considerable support from a shallow stiff web.

The resistance of the girder against buckling consists of the lateral stiffness of the web plus the lateral stiffness of the flange. The force causing buckling is the compression in the flange tending to bend it laterally. If it be assumed that buckling has occurred, then it is possible to calculate the work done by the compressive force on the flange and also the resilience of the deflected flange and web,[1] as was shown by Mr. S. Timoshenko.[2] Equating these two quantities, it is found that the critical stress for equilibrium is given by the formula

$$f_c = \frac{E}{A}\left(\frac{I_F \pi^2}{L^2} + \frac{t^3 L^2}{4h^3\pi^2}\right), \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where E denotes Young's modulus for the material, and f_c denotes the compressive stress in the flange.

Fig. 3.



The term $\frac{EI_F\pi^2}{AL^2}$ represents the stiffness of the flange, and the term $\frac{Et^3L^2}{4Ah^3\pi^2}$ represents the stiffness of the web. If the second term is neglected, the remainder is Euler's formula. This fact to a certain extent justifies the conventional use of a strut-formula, but it remains to be seen whether the second term is, in all cases, a negligible quantity.

[1] Appendix I.

[2] "Elastic Stability in Structures," Trans. Am. Soc. C.E., vol. 94 (1930), p. 1003.

End-Fixity.

Formula (1) represents the stability of a girder having rigid end-posts. If, however, the end-posts were as flexible as the rest of the web, the failure of the girder would take the form shown in *Fig. 3*. The total deflection of the compression-flange will still be y_o, but the maximum deflections of the web would be y_m and y_e, so that in this case its resistance would be considerably decreased.[1] In order to determine the ratio of y_e/y_m, it is necessary to find the condition of least resilience, by differentiating the expression representing the resilience with respect to y_e, equating it to zero and solving the resulting equation for y_e. Equation (1) then becomes:

$$f_c = \frac{E}{A}\left(\frac{I_F \pi^2}{L^2} + \frac{0{\cdot}19 t^3 L^2}{4h^3\pi^2}\right) \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

It will be seen that the second term is reduced by 81 per cent. If the ends of the flange were partially fixed, a value between 0·19 and unity would be required to meet the conditions. Fairly heavy end-stiffeners are used in the majority of girders, and one flange-plate is carried around the outside to form an end-post, which is rigidly connected to a bearing and which, in turn, possesses a high degree of fixity when the full-load reaction comes upon it. Under such conditions, it may safely be assumed that the ends of the compression-flange are fixed in position. Formula (1a) should not be used unless the end-posts of the girder are definitely of light construction.

The Wave-Length of the Flange.

The effect of end-fixity is modified by the form of failure of the compression-flange. The reason for this is as follows. If a strut is partially restrained by elastic lateral forces there is a tendency for it to fail in wave-form. This type of failure occurs in outstanding flanges of compression-members, where it is called "wrinkling," the wave-length being quite small. When a compression-flange fails in wave-form, the waves are of considerable length as shown in *Figs. 4 (a)*. When the wave-length is less than half the actual length of the flange, however, end-fixity becomes a negligible factor, and in order to find the wave-length of a compression-flange under these conditions, equation (1) must be differentiated with respect to L, and equated to zero:

Then $$L_w = \sqrt[4]{\frac{4\pi^4 h^3 I_F}{t^3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

[1] Appendix II.

Substituting the value of L_w for L in equation (1), the expression becomes

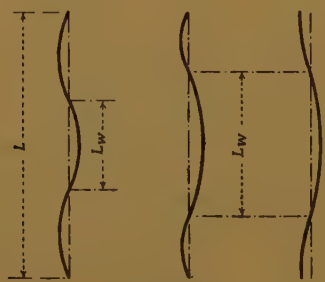
$$f_w = \frac{E}{A}\sqrt{\frac{I_F t^3}{h^3}} \quad \ldots \ldots \ldots \quad (3)$$

where f_w is the critical stress for a flange which has buckled in wave-form. If, however, L_w is greater than L, the critical stress is given by equation (1).

Loading-Coefficients.

It has been assumed that the compressive force in a flange is constant along its whole length, but under normal conditions bridge-girders are loaded with both uniformly-distributed and concentrated-

Figs. 4.



loads. It is therefore necessary to consider the effect of the type of loading on the stability of the compression-flange. In order to obtain equation (1) it was necessary to calculate the work done by the compressive force in the flange. If the force varies in accordance with a known condition, it is possible to obtain a revised value for the work done. Equation (1) may then be written as

$$f_c = \frac{KE}{A}\left(\frac{I_F \pi^2}{L^2} + \frac{t^3 L^2}{4h^3\pi^2}\right) \quad \ldots \ldots \quad (1b)$$

Table I.

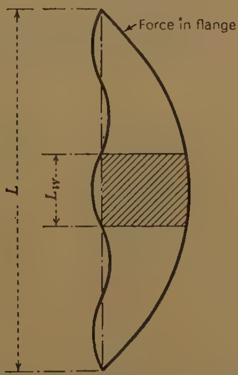
Type of loading.	Value of K.
Uniformly-distributed load	2·16
Central point-load	3·37
Loads at one-third points of the girder	2·27
Loads at one-quarter points of the girder	1·82

where K is the loading-coefficient.[1] The values of K are given in Table I.

It will be seen from Table I that, for maximum stability, the load should be concentrated at the centre of the girder, and as the loads are moved towards the ends, the loading-coefficient approaches nearer to unity, which is the coefficient for uniform force in the flanges.

The coefficients in Table I do not apply to formula (3), because it is necessary to consider the force in the flange within the limits of one wave-length. When the wave-length is small, the force within the wave is more nearly uniform and the loading-coefficient

Fig. 5.



approaches nearer to unity, as shown in *Fig. 5*, for a girder carrying a uniformly-distributed load. Table II gives the values of the

TABLE II.

Ratio $\frac{\text{wave-length}}{\text{flange-length}}$.	Value of K_w (calculated by method of Appendix III).
1·0	2·16
0·9	1·77
0·8	1·52
0·7	1·36
0·6	1·24
0·5	1·16
0·4	1·09
0·3	1·05
0·2	1·02
0·1	1·005

[1] Appendix I.

coefficient K_w for various ratios of $\frac{L_w}{L}$ with a uniformly-distributed load in the formula :

$$f_w = \frac{K_w E}{A} \sqrt{\frac{I_F t^3}{h^3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3a)$$

Stiffeners.

In the design of bridge-girders the web is almost invariably strengthened by angle- and gusset-stiffeners, which are riveted to the web- and cross girders and are usually fitted under the compression-flange, so that it is not possible for the compression-flange to buckle without deflecting the stiffeners. If the moment of inertia of the stiffener-sections be compared with the moment of inertia of the web-section, it is found that in most practical cases the lateral stiffness of the web is negligible. The critical buckling stress may be expressed by

$$f_c = \frac{KE}{A}\left(\frac{I_F \pi^2}{L^2} + \frac{3 I_s L^2}{d_s h^3 \pi^2}\right) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where I_s denotes the moment of inertia of a pair of stiffeners about an axis in the plane of the web, and d_s the spacing of the stiffeners.

The stiffening of the web results in a considerable decrease in the flange wave-length, which is given by

$$L_w = \sqrt[4]{\frac{\pi^4 d_s h^3 I_F}{3 I_s}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The critical stress for a flange which has buckled in a wave-form then becomes

$$f_w = \frac{K_w E}{A} \sqrt{\frac{12 I_F I_s}{d_s h^3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Generally, the wave-length of stiffened girders is smaller than the actual flange-length, so that expression (4) is not often used.

Flange-Plate Curtailment.

In most large plate-girders it is usual to curtail some of the flange-plates so that the flange-area at the ends is less than at midspan. This has the effect of reducing the lateral stiffness of the flange where the curtailment occurs, and an allowance for the reduction should be made in the formula. If each plate of the flange be considered individually, an effective moment of inertia for the whole may be calculated by adding together the effective inertias of the separate plates. Table III shows the value of coefficients m which, when multiplied by the moment of inertia of a plate of given curtailment, will give this effective moment of inertia. The total

effective moment of inertia of the flange is given by ΣmI_F and this value should be used for I_F in equations (4) and (6). If L_w is small, m will generally be unity for each plate, so that, for a girder of small wave-length, flange-curtailment may be neglected.

Referring to expression (5), it is clear that, at the ends of a girder, where I_F and d_s are always smaller than at midspan, the wave-length will also be smaller, so that the deflection-curve will probably be as in *Fig. 4* (*b*), and the critical section will then be the middle wave-length where the thrust is greatest. If the ends are not held in position the deflection-curve will probably be as shown in *Figs. 4* (*c*), and the middle wave will still be as shown in *Figs. 4* (*b*).

TABLE III.

Ratio of $\frac{\text{Length of flange-plate}}{\text{Overall length of flange or wave-length}}$.	Value of m (calculated by method of Appendix IV).
0·9	0·998
0·8	0·99
0·7	0·96
0·6	0·90
0·5	0·82
0·4	0·70
0·3	0·56
0·2	0·39
0·1	0·20

Form of Compression-Flange.

The compression-flange of a plate-girder usually consists of two angles riveted to the web, with flange-plates riveted to them. The centroid of a section of this kind usually lies near the backs of the angles, and, for the purpose of determining the dimension h in *Fig. 2* the distance between the centre line of the cross-girder connection and the backs of the flange-angles is sufficiently accurate. If, however, the flange has additional side-plates and extra stiffening-angles on the flange-plates, the centroid of the section should be determined. The use of stiffening-angles on the flange will considerably increase its lateral stiffness. This extra stiffness is allowed for in the British Standard Specification for Girder Bridges (Part 3, Clause 18), but, according to the formula suggested, a 3-inch by 3-inch angle is quite as effective as a 6-inch by 6-inch angle; this is obviously wrong. Increased stability may be obtained by increasing the breadth of the flange-plates, but there is a limit to the breadth of the flange owing to the liability of outstanding plates to wrinkle. Provided that the section of the flange is symmetrical about the plane of the web, the value of its moment of inertia substituted in the

formulas given in this Paper will make an accurate allowance for its form.

Secondary Stresses.

The foregoing formulas are based on the assumption that the flanges of the girders are always perfectly straight and symmetrical, and that the load is applied axially without any transverse twisting of the main girder. These conditions seldom occur in practice and it is necessary to consider the possible occurrence of secondary stresses.

Slightly eccentric and bent flanges are a common occurrence, due either to faulty workmanship or erection. Any fault of this kind will cause secondary stresses in the compression-flange, although in good-class work they will probably not exceed 5 or 10 per cent. of the main stress.

When a live load passes over the deck a deflection of the cross

Fig. 6.

girders will occur, their ends will become inclined, and there will be a tendency for the compression-flange to deflect inwards as shown on *Fig. 6.* The bending stress induced in the compression-flange by the passing of a load W, uniformly distributed over the whole of the deck, is given approximately by the formula [1]

$$f_{b_1} = \frac{W h d_c b L_c^2}{3{\cdot}5 L^3 I_c} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where L_c denotes the length of the cross girders.
I_c „ „ moment of inertia of the cross girders.
d_c „ „ spacing of the cross girders.
b „ „ breadth of the compression-flange.

[1] Derived in Appendix V.

It will be noted that the stress is proportional to the breadth of the flange and inversely proportional to the length, so that, in short bridge-girders with broad flanges, the secondary stress may be considerable unless slip occurs in the connections.

Secondary stresses may also be caused by transverse wind-forces acting normal to the web of the girder. The bending stress induced by a normal wind-force P_w, uniformly distributed over the whole web, is given approximately by the formula [1]

$$f_{b_2} = \frac{P_w L}{Z_F} \times \frac{1}{21 \cdot 4\left(1 + n^4 - 2n^2 \frac{f}{f_w} \times \frac{K_w}{K}\right)}, \quad . \quad . \quad (8)$$

where Z_F denotes the modulus of the flange, which is $\frac{2I_F}{b}$,

n „ „ ratio $\frac{L}{L_w}$,

f „ „ main compression-stress in the flange.

The stress f_{b_2} is usually fairly low.

Safe Working-Stress.

The combined stresses in the compression-flange should not exceed the safe working-stress plus such allowance as may be made for wind and occasional forces. The safe working-stress must not exceed the specified working-stress for the material, and where the critical stress divided by the factor of safety is less than this stress, allowance for buckling must be made. The factor of safety must cover all accidental eccentricity-stresses and faults in materials or workmanship. For good-class structural work, and especially in big structures where the ratio of live load to dead load is small, a factor of 2·0 on the yield-stress or buckling-stress should be sufficient if full allowance has been made for secondary stresses.

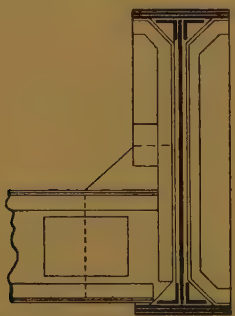
Errors in the Formula.

In most theoretical formulas errors are bound to arise from the inaccuracy of the assumptions. The preceding formulas are based on the assumption that the deflection-curve is sinusoidal, which is only true under the ideal conditions which were originally assumed. Under ordinary conditions the error arising from this cause will probably be not more than 5 per cent., especially when the ratio n is greater than 2. It is also assumed that the connections between the stiffeners and the cross girders are rigid,[2] and that the

[1] Derived in Appendix VI.
[2] Appendix VII.

girders themselves are homogeneous and follow Hooke's law. It is highly improbable in practice that either of these assumptions is strictly true, and any divergence from absolute rigidity or homogeneity will lead to a reduction of stability under load. However, the reduced stability will probably be fully compensated by the reduction of secondary stresses which is bound to result from slip in the connections. Provided the connections have a reasonable degree of rigidity the safe loads will probably vary only a little from those given by the formulas, although the actual distribution of stress may be different. To illustrate the application of the formulas and Tables, two examples have been taken from actual designs, one

Fig. 7.



of English and the other of American origin. In the first part of the calculation the restraint of the stiffeners is neglected, and in the second part their effect is clearly demonstrated.

Examples.

Example 1.

The girder selected was of English design, and was in accordance with the British Standard Specification for Girder Bridges. It had the following dimensions (*Fig. 7*):

Length overall	80 feet.
Depth to back of flange-angles . .	8 feet ¼ inch.
Depth of cross girders	3 feet.
Top flange-plate	2 feet 6 inches by ¾ inch by 43 feet long.
Middle flange-plate	2 feet 6 inches by ¾ inch by 54 feet ,,
Bottom flange-plate	2 feet 6 inches by ¾ inch by 80 feet ,,
Flange-angles	8-inch by 8-inch by ⅞-inch angles.
Thickness of web	¾ inch.
Stiffener-angles.	Four 5-inch by 3½-inch by ⅜-inch angles.
Stiffener-gussets	Two 1-foot 2-inch by ½-inch plates.
Centres of stiffeners	5 feet 3 inches.
Ratio L/b	32.

There were extra stiffeners near the supports, but, as will be shown later, they had no effect on the stability of the compression-flanges.

Neglecting in the first place the effect of the stiffeners, the critical length of flange may be calculated as follows. Let it be assumed that the free depth of the web is the distance between the top flange and the middle of the cross girders.

Since $\begin{cases} \text{the depth } h \text{ of the web is } 96 - 18 = 78 \text{ inches,} \\ \text{the gross moment of inertia } I_F \text{ of the flange-section} = 5{,}416 \\ \quad \text{inch}^4 \text{ units,} \\ \text{the gross area } A \text{ of the flange-section} = 100 \text{ square inches,} \end{cases}$

then the wave-length, as calculated from equation (2), is 1,240 inches. This is in excess of the actual length (960 inches) so that the latter value must be substituted for L in equation (1b). Allowance must now be made for the curtailment of the flanges, and this is done by finding the effective moment of inertia of the flange in the following manner.

The angles and one plate continue right through, so that their total moment of inertia is included; the middle flange-plate has a length of 54 feet, which is 0·68 of the total length. Referring to Table III, it will be found that the coefficient for a plate-length of 0·68 of the total length is 0·95. The moment of inertia of this plate should therefore be multiplied by 0·95. The top plate has a length of 43 feet, which is 0·54 of the total length; this gives a coefficient of 0·86. The effective moment of inertia of the whole flange is the sum of the modified values thus obtained, and in this case amounts to 5,087 inch^4 units, as against 5,416 inch^4 units gross. The loading coefficient is 2·16 (from Table I).

The value of the critical stress may now be calculated from equation (1b) using the dimensions given and assuming a value of Young's modulus of 13,000 tons per square inch; it is found to be

$$f_c = 21{\cdot}2 \text{ tons per square inch.}$$

The allowable stress, as given in the B.S.S. referred to above (Part 3, Clause 18), is, by the formula $f_s = 9\left(1 - 0{\cdot}01\,\frac{L}{b}\right)$, 5·8 tons per square inch. The factor of safety, neglecting stiffeners, is therefore 3·7.

The above calculations are worked out on the assumption that the stiffeners do not restrain the compression-flange. The following calculation shows how completely the provision of large stiffeners alters the stability of the girder.

The gross moment of inertia of a pair of stiffeners is 1,204 inch^4

units and their spacing is 63 inches. The effective depth of the web must be taken from the top of the cross girder in such cases where the stiffener is connected directly to the top flange of that girder, so that $h = 96 - 36 = 60$ inches. Using these amended figures, the wave-length, as calculated from equation (5), becomes 210 inches, and since this is less than the length of the girder, equation (6) must be used in calculating the critical stress. The wave-length is less than the length of the shortest plate so that the gross moment of inertia, 5,416 inch^4 units, must be used. The wave-length is, however, only 0·22 of the total length of the girders, so that the loading coefficient is no longer 2·16 as before but must be again taken from Table II; it is found to be 1·03. The critical stress under these conditions would be 318 tons per square inch. This, however, is a fictitious figure, and only serves to show that the girder will not fail by flange-buckling. The neglect of the additional end-stiffeners is justified by the fact that they lie outside the 210-inch mid-span wave-length, where the force causing buckling is greatest.

It is evident from these figures that the provision of stiffeners, although possibly necessary from considerations of shear and web-buckling, is not necessary from the point of view of flange-stability, and it would seem that some account ought to be taken of the restraint exercised by stiffeners if greater economy in design is to be obtained.

Example 2.

An American plate-girder of light design has been chosen for this example, the details being taken from an engineering journal. Its dimensions are as follows (*Fig. 8*):

Length overall	109 feet 0 inches.
Depth to back of flange-angles	9 feet 6 inches.
Depth of cross girders	2 feet 3 inches.
Top flange-plates	18 inches by $\frac{13}{16}$ inch by 45 feet.
Second flange-plate	18 inches by $\frac{13}{16}$ inch by 60 feet.
Third flange-plate	18 inches by $\frac{13}{16}$ inch by 70 feet.
Bottom flange-plate	18 inches by $\frac{13}{16}$ inch by 109 feet.
Flange-angles	6-inch by 6-inch by $\frac{7}{8}$-inch angles.
Side plates	16 inches by $\frac{7}{8}$ inch.
Thickness of web	$\frac{7}{16}$ inch.
Stiffener-angles	Two 5-inch by $3\frac{1}{2}$-inch by $\frac{3}{8}$-inch angles.
Centres of stiffeners	6 feet.
Ratio L/b	73.

Neglecting stiffeners and using an effective depth of web of 100 inches, the wave-length is 1,660 inches. The actual length is, however, only 1,308 inches, which must be used in the calculations for the critical stress. The gross moment of inertia of the flange is

1,822 inch^4 units, but the effective moment of inertia, taking into account the flange-plate curtailment as in the last example, is 1,625 inch^4 units, the flange area being 113 square inches. The critical stress, using a loading-coefficient of 2·16 and assuming Young's modulus to be 13,000 tons per square inch, is only 3·25 tons per square inch.

The effect of the stiffeners may now be considered. The moment of inertia of a pair of stiffeners is 62·2 inch^4 units, and their effective depth may be taken as 100 inches, as only every other stiffener is restrained by a cross girder. The wave-length of the compression-flange is 512 inches, from equation (5). This is 0·39 of the total flange-length, so that the loading coefficient is 1·08. The shortest plate is 540 inches, which is more than the wave-length, so that the

Fig. 8.

effective moment of inertia is 1,822 inch^4 units. The value of the critical stress, using these amended figures in equation (6), then becomes 17·0 tons per square inch.

The safe compressive stress, as calculated from the American formula $f_s = \dfrac{20{,}000}{1 + \dfrac{L^2}{2{,}000 b^2}}$, is 2·44 tons per square inch.

Conclusion.

The foregoing examples are sufficient to demonstrate that the present methods of designing the compression-flanges of through-bridge girders are inadequate to meet the conditions of all or even any case met with in practice. To estimate accurately the stability of a strut without any reference to the restraint of adjoining members

is impossible in all circumstances. Moreover, in some cases, adjoining members are connected to it along its whole length. If greater economy is to be attained in the design, the following points will require more careful consideration :

(1) *Dimensions of the Girder :* The stability of the compression-flange is dependent on the depth of the girder and on the stiffness of the web. The breadth of the flange is not of more importance than these two quantities.

(2) *End-Posts :* It is important that a girder should be provided with stout end-posts rigidly attached to the bearings, particularly when the ratio L/L_w is small.

(3) *Stiffeners :* The provision of very light stiffeners on the web of the girder adds very considerably to the stability of the compression-flange. Heavy stiffeners will generally ensure complete stability.

(4) *Connections of Cross Girders :* It is most important that the connection between the cross girders and the main girder should be rigid.

(5) *Type of Loading :* The shape of the bending-moment diagram determines the distribution of force in the compression-flange, and it has therefore a considerable influence on the stability of the girder, especially when the wave-length is large.

(6) *Flange-Plate Curtailment :* The curtailment of flange-plates reduces the resistance of the flange against lateral buckling. When the wave-length is large, this matter should be considered.

(7) *Live Loads on the Deck :* The provision of rigid connections between the cross girders and the main girder renders the latter liable to torsional deflection when live loads pass over the deck. The additional stresses induced in the compression-flange must be allowed for in the design.

(8) *Wind-Loads :* The stresses induced by normal wind-forces acting on the side of the girder may be calculated, and if they exceed the wind-stress allowance, additional strength must be provided to resist them. This, however, is not often necessary.

(9) *Straightness of Flanges :* Unless great care is taken in the fabrication and erection, the flanges of girders may not be truly straight. This applies particularly to braced girders, but even in plate-girders slight curvature sometimes occurs. When the wave-length is small, the eccentricity will be negligible ; when, however, it is large, transverse stresses to the extent of 10 per cent. of the main stress may be set up, and these must necessarily be covered by the factor of safety, as they cannot be anticipated in the design.

(10) *Welded Construction :* The theory will be more accurate for an all-welded construction, since no slip will occur in the connections

of the cross girders or between the component parts of the main girder. There will, however, be no relief, due to slip, from secondary stress within the limit of the yield-stress. In addition, the effect of impact is likely to be more pronounced.

(11) *High-Tensile Steel:* When high-tensile steel is substituted for mild steel there will be a consequent reduction in the size of the various members, and this renders more necessary an investigation into the elastic stability of such members. It will be found that, under similar conditions, for a given bending moment broader flanges or stiffeners are necessary when high-tensile steel is used than when mild steel is employed.

References.

References to the problem discussed in this Paper may be found in the following publications :—

British Standard Specification for Girder Bridges, No. 153 (1923), Part 3 (Loads and Stresses), and Part 4 (Details of Construction).

Arrol's "Bridge and Structural Engineer's Handbook" (1928), p. 74.

S. Timoshenko, "Elastic Stability of Structures," Trans. Am. Soc. Civil Engineers, vol. 94 (1930), p. 1003, *et seq.*

The Paper is accompanied by four sheets of diagrams, from which the Figures in the text and Appendixes have been prepared, and by the following Appendixes.

APPENDIX I.

Let AOB represent the centre line of a compression-flange (*Fig. 1*) which has suddenly buckled when the thrust has reached a critical value P. Consider a short length of flange δs. This length, measured along the original line of action of P, is δx, so that the shortening of the element along that line is $\delta s - \delta x$, and the total shortening of the flange will be $\Sigma(\delta s - \delta x)$.

Now
$$(\delta s)^2 = (\delta x)^2 + (\delta y)^2,$$
$$\therefore \frac{\delta s}{\delta x} = \sqrt{1 + \left(\frac{\delta y}{\delta x}\right)^2}$$

In the limit where
$$\delta s \to ds, \frac{ds}{dx} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2}$$
$$= \tfrac{1}{2}\left(\frac{dy}{dx}\right)^2 + 1$$

or
$$\frac{ds}{dx} - 1 = \tfrac{1}{2}\left(\frac{dy}{dx}\right)^2.$$

The work done by the thrust P (assumed constant) will be

$$W_k = P\Sigma(\delta s - \delta x) = P\Sigma\left(\frac{\delta s}{\delta x} - 1\right)\delta x$$

whence
$$W_k = P\int \tfrac{1}{2}\left(\frac{dy}{dx}\right)^2 dx.$$

Assuming that the curve AOB is sinusoidal, then the deflection at any point distant x from the origin O will be

$$y = y_0 \cos \frac{\pi x}{L},$$

where y_0 is the deflection at the origin.

Then
$$\left(\frac{dy}{dx}\right)^2 = \frac{\pi^2 y_0^2}{L^2} \sin^2 \frac{\pi x}{L}.$$

Hence
$$W_k = P\int_{-\frac{L}{2}}^{\frac{L}{2}} \tfrac{1}{2}\frac{\pi^2 y_0^2}{L^2} \sin^2 \frac{\pi x}{L} dx$$
$$= \frac{P\pi^2 y_0^2}{2L^2}\left[x - \frac{L}{2\pi}\cos\frac{2\pi x}{L}\right]_{-\frac{L}{2}}^{\frac{L}{2}}$$
$$= \frac{P\pi^2 y_0^2}{4L} \quad \ldots \ldots \ldots \ldots \quad (10)$$

The resilience of the bent flange may now be considered.

Then
$$R_F = \tfrac{1}{2}EI_F \int_{-\frac{L}{2}}^{\frac{L}{2}} \left(\frac{d^2y}{dx^2}\right)^2 dx$$

Now $$\frac{dy}{dx} = -y_0 \frac{\pi}{L} \sin \frac{\pi x}{L}, \text{ and } \frac{d^2y}{dx^2} = -y \frac{\pi^2}{L^2} \cos \frac{\pi x}{L}$$

and ∴ $$R_F = \frac{EI_F y_0^2 \pi^4}{2L^4} \int_{-\frac{L}{2}}^{\frac{L}{2}} \cos^2 \frac{\pi x}{L} dx$$

$$= \frac{EI_F \pi^4 y_0^2}{4L^3} \quad \ldots \ldots \ldots \ldots \ldots \quad (11)$$

Fig. 2 represents a web which is being bent over by the lateral buckling force of a compression-flange. Consider a strip of the web, of width dx and of length h, as a cantilever fixed at the bottom flange. Assume that the force at the top is dF and that the deflection due to dF is y.

Then $$dF = \frac{3Ey}{h^3} \times \frac{1}{12} t^3 dx.*$$

The resilience of the bent strip is

$$dR_w = \tfrac{1}{2} y dF$$

$$= \tfrac{1}{2} y \frac{Eyt^3dx}{4h^3}$$

$$= \frac{Et^3y^2dx}{8h^3} \quad \ldots \ldots \ldots \quad (12a)$$

The total resilience of the bent web is

$$R_w = \frac{Et^3y_0^2}{8h^3} \int_{-\frac{L}{2}}^{\frac{L}{2}} \cos^2 \frac{\pi x}{L} dx$$

$$= \frac{1}{16} \frac{Et^3y_0^2L}{h^3} \quad \ldots \ldots \ldots \quad (12)$$

Now, neglecting the deflection due to shear and direct compression, the work done on the flange by the direct force is equal to the resilience of the bent flange and web, so that

$$W_k = R_F + R_w.$$

For a girder with uncurtailed flange-plates and no stiffeners on the web, the equation for equilibrium is

$$\frac{P\pi^2y_0^2}{4L} = \frac{EI_F \pi^4 y_0^2}{4L^3} + \frac{1}{16} \frac{Et^3y_0^2L}{h^3}$$

Therefore

$$P = \frac{EI_F \pi^2}{L^2} + \frac{Et^3L^2}{4h^3\pi^2} \quad \ldots \ldots \ldots \quad (13)$$

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* A more exact expression would be $\frac{3Ey}{h^3} \times \frac{1}{12} \frac{t^3dx}{(1-\sigma^2)}$ where σ is Poisson's ratio. As, however, all plate-girders for bridges have web-stiffeners, the stiffness of the web need not be calculated to any great degree of accuracy, so that $(1-\sigma^2)$ has been omitted.

Let A be the area of the compression flange; then the buckling stress

$$f_c = \frac{E}{A}\left(\frac{I_F \pi^2}{L^2} + \frac{t^3 L^2}{4h^3\pi^2}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The condition of critical stress occurs when the quantity $\frac{df_c}{dL}$ equals zero; that is

$$\frac{df_c}{dL} = \frac{-2EI_F\pi^2}{AL^3} + \frac{2Et^3L}{4A\pi^2h^3} = 0$$

$$\therefore \qquad L_w = \sqrt[4]{\frac{4\pi^4 h^3 I_F}{t^3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Substituting this value for L in equation (1),

$$f_w = \frac{E}{A}\sqrt{\frac{I_F t^3}{h^3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

For a girder subjected to a uniformly-distributed load, P is a variable and is expressed by the equation

$$P = P_o\left(1 - \frac{4x^2}{L^2}\right)$$

where P_o is the force at O.

Hence, $$W_k = P_o\int_{-\frac{L}{2}}^{\frac{L}{2}}\left(\frac{\pi^2 y_o^2}{2L^2} \cdot \sin^2\frac{\pi x}{L} - \frac{2x^2\pi^2 y_o^2}{L^4}\sin^2\frac{\pi x}{L}\right)dx$$

$$= \frac{P_o y_o^2 \pi^2}{L^2}\left[\frac{x}{4} - \frac{L}{8\pi}\sin\frac{2\pi x}{L} - \frac{x^3}{3L^2} + \frac{x^2}{2\pi L}\sin\frac{2\pi x}{L} + \frac{x}{2\pi^2}\cos\frac{2\pi x}{L} - \frac{L}{4\pi^3}\sin\frac{2\pi x}{L}\right]_{-\frac{L}{2}}^{\frac{L}{2}}$$

$$= \frac{P_o y_o^2 \pi^2}{L^2}\left(\frac{L}{4} - \frac{L}{12} - \frac{L}{2\pi^2}\right)$$

$$= \frac{1}{2{\cdot}16} \cdot \frac{P_o \pi^2 y_o^2}{4L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14a)$$

And for any given loading

$$W_k = \frac{P_o \pi^2 y_o^2}{4KL} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Comparing equation (10) with equation (14a) it will be seen that they are the same except for the coefficient 2·16, which is the loading-coefficient for a uniformly-distributed load. The loading-coefficients for other types of loading may be calculated in a similar manner, as set out in Table I.

It is to be noted that the deflection-curve is only strictly sinusoidal for a uniform thrust, uniform lateral support from the web or stiffeners and uniform inertia of the flange. In the above and succeeding variations from these conditions errors are introduced, but such errors are of the order of 5 per cent. only.

APPENDIX II.

Where the ends of the compression-flange are not laterally fixed in position, the resilience of deflection of the web will be modified. Its lateral deflection with reference to the tension-flange is now represented approximately by

$$y = y_0 \cos \frac{\pi x}{L} - y_e. \qquad \text{(See } Fig.\ 3$$

Also $$dR_w = \frac{Et^3y^2}{8h^3}dx, \qquad \text{(from (12a))}$$

Hence $$R_w = \frac{Et^3}{8h^3}\int_{-\frac{L}{2}}^{\frac{L}{2}}\left(y_0 \cos \frac{\pi x}{L} - y_e\right)^2 dx$$

$$= \frac{Et^3}{8h^3}\left[\frac{y_0{}^2x}{2}\frac{Ly_0{}^2}{4\pi} \sin \frac{2\pi x}{L} - \frac{2y_ey_0L}{\pi} \sin \frac{\pi x}{L} + y_e{}^2\right]_{-\frac{L}{2}}^{\frac{L}{2}}$$

$$= \frac{Et^3}{8h^3}\left(\frac{y_0{}^2L}{2} - \frac{4y_ey_0L}{\pi} + y_e{}^2L\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(15a)}$$

In order to find the value of y_e for minimum resilience, this expression must be differentiated with respect to y_e and equated to zero.

Then $$\frac{dR_w}{dy_e} = \frac{Et^3}{8h^3}\left(-\frac{4y_0L}{\pi} + 2y_eL\right) = 0,$$

and hence $$y_e = \frac{2y_0}{\pi}.$$

Then, substituting for y_e in equation (15a)

$$R_w = \frac{Et^3}{8h^3}\left(\frac{y_0{}^2L}{2} - \frac{8y_0{}^2L}{\pi^2} + \frac{4y_0{}^2L}{\pi^2}\right)$$

$$= \frac{1}{16}\cdot\frac{Et^3Ly_0{}^2}{h^3} \times 0{\cdot}19 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(15)}$$

Then $$f_c = \frac{E}{A}\left(\frac{I_F\,\pi^2}{L^2} + \frac{0{\cdot}19t^3L^2}{4h^3\pi^2}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(1a)}$$

The critical length $$L_w = \sqrt[4]{\frac{4\pi^4h^3I_F}{0{\cdot}19t^3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(2a)}$$

and for a beam of length L_w, $$f_w = \frac{E}{A}\sqrt{\frac{0{\cdot}19I_F\,t^3}{h^3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(3a)}$$

Formula (3a) applies only to a girder of length L_w, but if the length is much greater than L_w, f_w will be as given in equation (3). For lengths slightly greater than L_w, f_w will be intermediate between the values obtained from (3) and (3a).

APPENDIX III.

Where the wave-length of the flange is shorter than the actual length, the value of W_k as deduced under (14) above will be modified.

If the ratio $$\frac{L_w}{L} = \frac{1}{n}, \text{ as in } Fig.\ 5,$$

then $$P = P_o\left(1 - \frac{4x^2}{n^2 L_w{}^2}\right).$$

$$\text{Hence, } W_k = \frac{P_o y_o{}^2 \pi^2}{L_w{}^2}\left[\frac{x}{4} - \frac{L_w}{8\pi}\sin\frac{2\pi x}{L_w} - \frac{x^3}{3L_w{}^2 n^2} + \frac{x^2}{2\pi n^2 L_w}\sin\frac{2\pi x}{L_w} + \frac{x}{2\pi^2 n^2}\cos\frac{2\pi x}{L_w} - \frac{L_w}{4\pi^3 n^2}\sin\frac{2\pi x}{L_w}\right]_{-\frac{L_w}{2}}^{\frac{L_w}{2}}$$

$$= \frac{P_o y_o{}^2 \pi^2}{4L_w}\left(1 - \frac{0{\cdot}536}{n^2}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

The expression $\frac{n^2}{n^2 - 0{\cdot}536}$ is the loading coefficient K_w, and may be calculated for various values of $\frac{L_w}{L}$ (Table II).

APPENDIX IV.

Where the flange-plates are in part curtailed, the value of R_F given under (12) should be modified for each flange-plate of curtailed length L_c by integrating between the limits of $\pm\frac{L_c}{2}$, so that

$$R_F = \frac{EI_F y_o{}^2 \pi^4}{4L^3}\left(\frac{L_c}{L} + \frac{1}{\pi}\sin\frac{\pi L_c}{L}\right) \quad . \quad . \quad . \quad . \quad . \quad (17)$$

Substituting various values of $\frac{L_c}{L}$, the curtailment-coefficients m may be obtained, as given in Table III.

APPENDIX V.

The lateral bending stress induced in the top flange by a live load on the cross girders may be calculated approximately as follows:

It is assumed that the cross girders are so stiff, as compared with the stiffeners and the compression-flange of the main girder, that when loads are applied the ends of the cross girders may be considered as unrestrained, and that they will take up the inclination of a simply-supported beam. If the connection of the cross girder to the stiffener is absolutely rigid, this inclination (i) is taken up by the bottom of the stiffeners, and the compression-flange will be deformed. It

is assumed that the end-stiffeners are held vertical by the reaction of the bridge on the bearings, while the end cross girders will probably receive support from the abutments.

If the deflection of the flange at any point is y, the actual distortion (*Fig. 6*) of a stiffener will be $ih - y$. The resilience of the bent stiffener will be $\frac{3EI_s}{2h^3}(ih - y)^2$, and the total resilience of all the stiffeners of one girder, assuming the moment of inertia I_s to be spread over the distance d_s, will be

$$R_s = \int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{3EI_s}{2h^3 d_s}(ih - y)^2 dx \quad \ldots \ldots \quad (18)$$

It is assumed that $y = y_0 \cos \frac{\pi x}{L}$ (that is, the curve is sinusoidal);

then $$R_s = \frac{3}{2}\frac{EI_s}{d_s h^3}\left(i^2h^2L - 4ihy_0\frac{L}{\pi} + y_0^2\frac{L}{2}\right) \quad \ldots \ldots \quad (19)$$

The work done (W_J) by the cross girder on the stiffeners will be $\frac{1}{2}iT$, where T is the torque. If F is the reaction of the stiffener on the compression-flange required to cause the distortion $ih - y$, than $T = hF$, and the work done on each stiffener will be $\frac{1}{2}ihF$.

Now F will be a maximum at the ends and a minimum at the centre, and it will be equal to $\frac{3EI_s}{h^3}(ih - y)$.

The total work done by all cross girders will be

$$W_J = \int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{3EI_s}{2d_s h^3} ih\left(ih - y_0 \cos \frac{\pi x}{L}\right)dx$$

$$= \frac{3}{2}\frac{EI_s}{d_s h^3}\left(i^2h^2L - 2ih\frac{L}{\pi}y_0\right) \quad \ldots \ldots \ldots \quad (20)$$

Neglecting the work done in twisting [1] the main girder, the energy-equation now becomes:

$W_k \times W_J = R_F + R_s$, as shown in (10) and (14).

Hence $$\frac{P\pi^2 y_0^2}{4KL} + \frac{3}{2}\frac{EI_s}{d_s h^3}\left(i^2h^2L - 2ih\frac{L}{\pi}y_0\right) = \frac{EI_F\pi^4 y_0^2}{4L^3} + \frac{3}{2}\frac{EI_s}{d_s h^3}\left(i^2h^2L - 4ih\frac{L}{\pi}y_0 + \frac{L}{2}y_0^2\right).$$

Hence $$\frac{P\pi^2 y_0^2}{4KL} = \frac{EI_F\pi^4 y_0^2}{4L^3} + \frac{3EI_s}{2d_s h^3} y_0\left(\frac{L}{2}y_0 - 2ih\frac{L}{\pi}\right).$$

from which $$y_0 = \frac{\frac{3LihEI_s}{\pi d_s h^3}}{\frac{EI_F\pi^4}{4L^3} + \frac{3}{4}\frac{EI_sL}{d_s h^3} - \frac{P\pi^2}{4KL}}.$$

---

[1] Appendix VII.

Then, dividing both top and bottom lines by $\dfrac{\pi^2}{4K_wL}$,

$$y_0 = \frac{\dfrac{12K_wL^2ihEI_s}{\pi^3d_sh^3}}{K_wE\left(\dfrac{I_F\pi^2}{L^2} + \dfrac{3I_sL^2}{\pi^2d_sh^3}\right) - P\dfrac{K_w}{K}} \quad . \quad . \quad . \quad . \quad (21)$$

Now if, as is generally the case, $\dfrac{L}{L_w}$ is greater than unity, K will become K_w,

and $\quad K_wE\left(\dfrac{I_F\pi^2}{L^2} + \dfrac{3I_sL^2}{\pi^2d_sh^3}\right) = f_wA\left(\dfrac{1}{2n^2} + \dfrac{n^2}{2}\right)$, from formulas (4) and (5),

where $\quad n = \dfrac{L}{L_w}.$

Also $\quad \dfrac{\pi^2K_wEI_F}{AL^2} = \dfrac{f_w}{2n^2},$

and $\quad f_w^2 = \dfrac{12K_w^2E^2I_FI_s}{d_sh^3A^2}$ (from formula (6).)

Substituting these values in (21),

$$y_0 = ih \times \frac{2n^2}{\pi\left(\dfrac{1}{2n^2} + \dfrac{n^2}{2} - \dfrac{fK_w}{f_wK}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

where f is the actual main bending stress in the flange.

The secondary stress f_b due to the deflection y_0 will be $\dfrac{b}{2}E\dfrac{d^2y}{dx^2}$, where b is the breadth of the flange, and since

$$y = y_0 \cos\frac{\pi x}{L},$$

$$f_b \max = \frac{b}{2}\frac{E\pi^2ih}{L^2} \times \frac{2n^2}{\pi\left(\dfrac{1}{2n^2} + \dfrac{n^2}{2} - \dfrac{f}{f_w}\cdot\dfrac{K_w}{K}\right)}.$$

For a uniformly-distributed live load over the whole of the deck,

$$i = \frac{Wd_cL_c^2}{24LEI_c}$$

where $\quad W$ denotes the live load on the whole deck.
$\quad L_c$ " length of the cross girders.
$\quad I_c$ " the moment of inertia of the cross girders.
$\quad d_c$ " the spacing of the cross girders.

$$\therefore f_{b_1} \max = \frac{\pi^2Wbhd_cL_c^2}{48L^3I_c} \times \frac{2n^2}{\pi\left(\dfrac{1}{2n^2} + \dfrac{n^2}{2} - \dfrac{f}{f_w}\cdot\dfrac{K_w}{K}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

where f_{b_1} is the secondary stress due to a load passing over the deck.

For a uniformly-distributed load $\dfrac{K_w}{K} = \dfrac{n^2}{2{\cdot}16(n^2 - 0{\cdot}536)}$ (Appendix III).

The second expression of formula (23) would then become

$$\frac{2n^2}{\pi\left(\frac{1}{2n^2}\times\frac{n^2}{2}-\frac{n^2 f}{2{\cdot}16(n^2-0{\cdot}536)f_w}\right)}.$$

The minimum safe value of the ratio $\frac{f}{f_w}$ is 2, and the maximum would not be greater than 50. Between these limits the maximum value of the expression for all values of n lies between 1·27 and 1·38, the maximum value being when $n = 1{\cdot}69$. The usual values of n lie between 1·25 and 3, for which the maximum value of the expression lies between 1·33 and 1·38. Therefore if the value of the expression be taken as 1·38, the error will not usually be great, and formula (23) reduces to

$$f_{b_1} = \frac{Wbhd_cL_c^2}{3{\cdot}5L^3I_c} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The secondary stresses due to the loads on the deck are usually small, but in cases where they are important it would be advisable to use formula (23) as a check.

APPENDIX VI.

It is assumed that the intensity of the wind-pressure is p pounds per square foot, acting normal to the web of the girder. Consider the stiffeners as cantilevers carrying a uniformly-distributed load due to the wind, and a concentrated load due to the lateral force of the compression-flange (*Fig. 9*).

If the vertical-deflection curve of the stiffeners is assumed to be sinusoidal, then

$$y_1 = y\left(1-\cos\frac{\pi z}{2h}\right).$$

The work done by the wind on a unit length of the girder

$$= \int_0^h \tfrac{1}{2}py_1 dz$$

$$= \tfrac{1}{2}py\int_0^h\left(1-\cos\frac{\pi z}{2h}\right)dz$$

$$= \frac{\pi-2}{2\pi}phy.$$

The total work done by the wind on the whole surface of the girder, where $y = y_0\cos\frac{\pi x}{L}$, will be

$$W_w = \int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{\pi-2}{2\pi}phy_0\cos\frac{\pi z}{L}dx, \text{ as shown in } \textit{Fig. 1},$$

$$= \frac{\pi-2}{\pi^2}phLy_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

Assuming that the rigidity of the stiffeners is spread over the whole of the web, so that the moment of inertia of a pair of stiffeners per unit length will be $\frac{I_s}{d_s}$, then the resilience R_s of all the stiffeners may be calculated by the same method as formula (12)

$$R_s = \frac{3}{4}\frac{EI_sLy_o^2}{d_sh^3} \qquad (25)$$

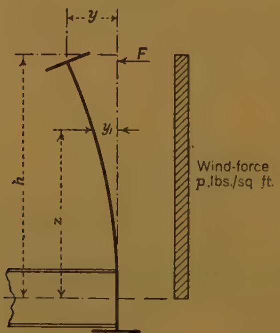
The energy-equation now becomes

$$W_k + W_w = R_F + R_s,$$

and therefore, from formulas (10) and (14),

$$\frac{P\pi^2y_o^2}{4KL} + \frac{\pi-2}{\pi^2}phLy_o = \frac{EI_F\pi^4y_o^2}{4L^3} + \frac{3}{4}\frac{EI_sLy_o^2}{d_sh^3}.$$

Fig. 9.



Solving this,

$$y_o = \frac{\frac{\pi-2}{\pi^2}phL}{\frac{EI_F\pi^4}{4L^3} + \frac{3}{4}\frac{EI_sL}{d_sh^3} - \frac{P\pi^2}{4KL}}.$$

Dividing both top and bottom lines by $\frac{\pi^2}{4K_wL}$,

$$y_o = \frac{\frac{(\pi-2)4K_wphL^2}{\pi^4}}{K_wE\left(\frac{I_F\pi^2}{L^2} + \frac{3I_sL^2}{\pi^2d_sh^3}\right) - \frac{PK_w}{K}}.$$

But $\frac{L_w}{L}$ will probably be greater than unity, so that K becomes K_w, and, by the method of Appendix V,

$$y_o = \frac{\frac{\pi-2}{\pi^4}4K_wphL^2}{f_wA\left(\frac{1}{2n^2} + \frac{n^2}{2}\right) - fA\frac{K_w}{K}}.$$

Since, however, $f_w = \frac{\pi^2 K_w E I_F}{AL^2} \cdot 2n^2$,

then
$$y_0 = \left(\frac{\pi - 2}{\pi^6}\right)\left(\frac{4phL^4}{EI_F}\right)\frac{1}{1 + n^4 - 2n^2 \frac{f}{f_w} \cdot \frac{K_w}{K}} \quad . \quad . \quad . \quad (26)$$

Also,
$$f_b = \frac{b}{2} E \frac{d^2y}{dx^2}, \text{ where } y = y_0 \cos \frac{\pi x}{L}$$

and hence
$$f_{b_2}\max = \frac{b}{2} E \frac{\pi^2}{L^2}\left(\frac{\pi - 2}{\pi^6}\right)\left(\frac{4phL^4}{EI_F}\right)\frac{1}{1 + n^4 - 2n^2 \frac{f}{f_w} \cdot \frac{K_w}{K}}$$

where f_{b_2} is the secondary stress due to the lateral wind-force,

which reduces to
$$\frac{P_w L}{Z_F} \cdot \frac{1}{21{\cdot}4\left(1 + n^4 - 2n^2 \frac{f}{f_w} \cdot \frac{K_w}{K}\right)} \quad . \quad . \quad . \quad . \quad (8)$$

where P_w denotes the total wind-force normal to the web of the girder,
Z_F ,, modulus of the compression-flange about the vertical axis $\left(= \frac{2I_F}{b}\right)$,
n ,, ratio of $\frac{L}{L_w}$,
f ,, main compression-stress in the flange.

APPENDIX VII.

The following analysis indicates the method which may be used to estimate the stability of a girder when the connections of the cross girders have no rigidity.

Let it be assumed in the first case that the stiffeners are rigid and that the whole of the displacement, y, of the compression-flange is due to rotation of the girder about the bottom of the web (*Figs.* 10 (a)). This rotation is equivalent to a lateral displacement $\frac{y}{2}$ of the whole girder and to a twist, θ, about the centroid.

The resilience of twisting about the centroid is as follows :—

$$R_J = \frac{GJ}{2}\int_{-\frac{L}{2}}^{\frac{L}{2}}\left(\frac{d\theta}{dx}\right)^2 dx$$

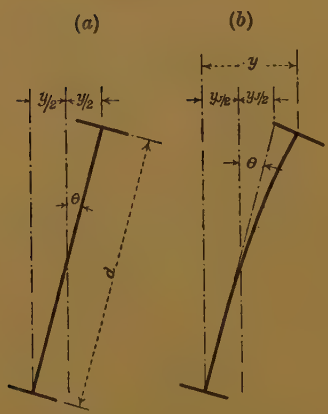
where GJ denotes the torsional stiffness of the girder-section.* For small values, $\delta\theta \frac{\delta y}{d}$, where d is the overall depth of the girder.

$$\therefore\ R_J = \frac{GJ}{2d^2}\int_{-\frac{L}{2}}^{\frac{L}{2}}\left(\frac{dy}{dx}\right)^2 dx, \text{ and if } y = y_o \cos\frac{\pi x}{L},$$

$$R_J = \frac{GJ}{2d^2}\int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{y_o^2\pi^2}{L^2}\sin^2\frac{\pi x}{L}dx$$

$$= \frac{GJ\pi^2 y_o^2}{4Ld^2} \quad \ldots \ldots \ldots \ldots \quad (27)$$

Figs. 10.



Substituting $\frac{y_o}{2}$ for y_o, and I_{yy} for I_F in formula (11),

$$R_G = \frac{EI_{yy}\pi^4}{4L^3}\cdot\frac{y_o^2}{4}.$$

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* Information on this matter is given by E. H. Salmon, "Materials and Structures," Vol. 1, p. 258, and in other similar works.

In the particular case where $\frac{EI_{yy}\pi^2}{4L^2} = \frac{GJ}{d^2}$, formula (28) may be written as $f_J = \frac{\pi K}{Ad}\sqrt{EI_{xx}GJ}$, which is the same form as Mitchell's formula for a laterally-unsupported beam, so that in this one instance the girder will not require lateral restraint from the deck. In all other cases there will be a lateral force acting on the bottom flange of the girder.

The energy-equation will now be written

$$W_k = R_G + R_J \text{ (from formula (14))},$$

and hence
$$\frac{P\pi^2 y_0^2}{4KL} = \frac{EI_{yy}\pi^4 y_0^2}{16L^3} + \frac{GJ\pi^2 y_0^2}{4Ld^2}.$$

Hence
$$\frac{P}{K} = \frac{EI_{yy}\pi^2}{4L^2} + \frac{GJ}{d^2}$$

and
$$f_J = \frac{K}{A}\left(\frac{EI_{yy}\pi^2}{4L^2} + \frac{GJ}{d^2}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

It should be noted in the first place that in (28) the term $\frac{GJ}{d^2}$ is independent of L, so that there is a limiting lower value of f_J dependent only on the torsional stiffness of the beam, and in the second place that the beam will not fail in wave-form.

If the ends of the compression-flange are not held in position the failure may be of the form indicated in *Fig. 3*. As in Appendix II,

$$y = y_0 \cos\frac{\pi x}{L} - y_e$$

and
$$R_J = \frac{GJ}{2d^2}\int_{-\frac{L}{2}}^{\frac{L}{2}}\left[\frac{d}{dx}\left(y_0 \cos\frac{\pi x}{L} - y_e\right)\right]^2 dx$$

$$= \frac{GJ}{2d^2}\int_{-\frac{L}{2}}^{\frac{L}{2}} y_0^2 \frac{\pi^2}{L^2} \sin^2\frac{\pi x}{L} \, . \, dx$$

$$= \frac{GJ\pi^2 y_0^2}{4Ld^2},$$

so that the rigidity of the end-posts of the girder will not affect the value of f_J.

The stiffeners, not being absolutely rigid, will in practice deflect, so that the lateral deflection of the compression-flange will be accompanied by twisting of the girder and bending of the web, as shown in *Fig. 10* (*b*). If the total displacement of the flange is y and the displacement due to twisting is y_J, the energy-equation will be

$$W_k = R_G + R_J + R_s \qquad \text{(see formula (25))}$$

Then
$$\frac{P\pi^2 y_0^2}{4KL} = \frac{EI_{yy}\pi^4 y_J^2}{16L^2} + \frac{GJ\pi^2 y_J^2}{4Ld^2} + \frac{3EI_s L(y_0 - y_J)^2}{4d_s d^3}.$$

Hence
$$f_{Js} = \frac{K}{A}\left(\frac{EI_{yy}\pi^2 y_J^2}{4L^2 y_0^2} + \frac{GJ y_J^2}{d^2 y_0^2} + \frac{3EI_s L^2(y_0 - y_J)^2}{\pi^2 d_s d^3 y_0^2}\right)$$

Differentiating with respect to y_J, equating to zero, and substituting, the least value of f_{Js} will be

$$\frac{K}{A}\left(\frac{EI_{yy}\pi^2}{4L^2} + \frac{GJ}{d^2}\right) \times \frac{\dfrac{3EI_s L^2}{\pi^2 d_s d^3}}{\dfrac{EI_{yy}\pi^2}{4L^2} + \dfrac{GJ}{d^2} + \dfrac{3EI_s L^2}{\pi^2 d_s d^3}} \quad . \quad . \quad . \quad (29)$$

The second part of the expression approaches unity for most practical cases, and the formula is then as in (28).

APPENDIX VIII.

Method of Design.

As a general rule, a girder of normal proportions and having the usual stiffeners will have a wave-length (L_w) of less than half of the actual length of the girder, so that formula (6) can generally be used and the value of K_w will be approximately unity.

In order to obtain an economical section for the compression-flange the value of f_w should be just greater than the yield-stress of the material; for example, f_w may be taken as 20 tons per square inch, so that formula (6) may be written

$$20 = \frac{13{,}000}{A}\sqrt{\frac{12 I_F I_s}{d_s h^3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

It has been found from a number of cases that I_F is approximately equal to $\frac{Ab^2}{15}$, so that substituting for I_F in (30) and solving for b,

$$b = \frac{1}{650}\sqrt{\frac{15 A d_s h^3}{12 I_s}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

Now, neglecting the area of the web,

$$A = \frac{12M}{fb} \text{(approximately)}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

where M denotes the applied bending moment in tons–feet.
d ,, ,, overall depth of the girder.
f ,, ,, the stress in the flanges.

Substituting for A in formula (31)

$$b = \frac{1}{650}\sqrt{\frac{15 M d_s h^3}{f d I_s}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Assuming a working-stress (f) of 9 tons per square inch, and also assuming that d_s is equal to d, which is often the case in the middle of a girder, then

$$b = \frac{1}{500}\sqrt{\frac{Mh^3}{I_s}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

The values of b will usually be rather high because the area of the web was neglected in formula (32).

Using high-tensile steel having a working-stress of 13·5 tons per square inch and a yield-stress of 30 tons per square inch, formula (34) becomes

$$b = \frac{1}{410}\sqrt{\frac{Mh^3}{I_s}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34a)$$

Thus, using the same depth and stiffeners, for a given moment of resistance a broader flange will be required for high-tensile steel than for mild steel.

For example, considering a girder of a highway-bridge of 80 feet span, having a 20-foot carriageway and 6-foot sidewalks, the loading on each girder will be:

Dead Load per Girder.

Steelwork (approximately)	=	530 pounds per foot run.
8-inch (average) concrete slab at 144 pounds per cubic foot = $\frac{8}{12} \times 144 \times 10$ feet	=	960 ,, ,, ,, ,,
3-inch tarmac at 144 pounds per cubic foot = $\frac{3}{12} \times 144 \times 10$ feet	=	360 ,, ,, ,, ,,
5-inch sidewalk at 144 pounds per cubic foot = $\frac{5}{12} \times 144 \times 6$ feet	=	360 ,, ,, ,, ,,
Concrete haunching, curbs, etc.	=	350 ,, ,, ,, ,,
Mains	=	250 ,, ,, ,, ,,
Open parapet	=	20 ,, ,, ,, ,,
		2,830 ,, ,, ,, ,,
	=	1·27 tons per foot run.

Live Load per Girder.

Road traffic on carriageway at 220 pounds per square foot = 220×10 feet	=	2,200 pounds per foot run.
100 pounds per square foot on sidewalks = 100×6 feet	=	600 ,, ,, ,, ,,
		2,800 ,, ,, ,, ,,
	=	1·25 tons per foot run.

(Assumed) concentrated load

$$= \frac{2{,}700 \times 10 \text{ feet}}{2{,}240} = 12 \text{ tons.}$$

Total distributed load $= (1·27 + 1·25) \times 80 = 201$,,

Maximum bending moment

$$= \frac{201 \times 80}{8} + \frac{12 \times 80}{4} = 2{,}250 \text{ foot-tons.}$$

Let it be assumed that the web is 7 feet deep and that the stiffeners are 4-inch by 3-inch by ⅜-inch angles at 7-foot centres, the cross girders being 22-inch by 7-inch by 75-pound R.S.J's. at 7-foot centres. The moment of inertia of a pair of stiffeners is 19·3 inch^4 units, and assuming h to be 6 feet, then using formula (34),

$$b = \frac{1}{500}\sqrt{\frac{2{,}250 \times 72^3}{19·3}} = 13·2 \text{ inches.}$$

Now designing the girder with an assumed breadth of flange of 13 inches,

	Gross flange-area	Moment of inertia
Two 5-inch by 5-inch by ⅞-inch angles	13·88	45,700
13-inch by 1⅞-inch plates	24·4	89,900
7-foot by ½-inch web	3·0 (approx.)	24,700
	41·28	160,300
Deducting rivet-holes		23,900
		136,400 inch^4 units.

Then net modulus

$= 3{,}100$ inch³ units. Gross modulus $= 3{,}650$ inch³ units.

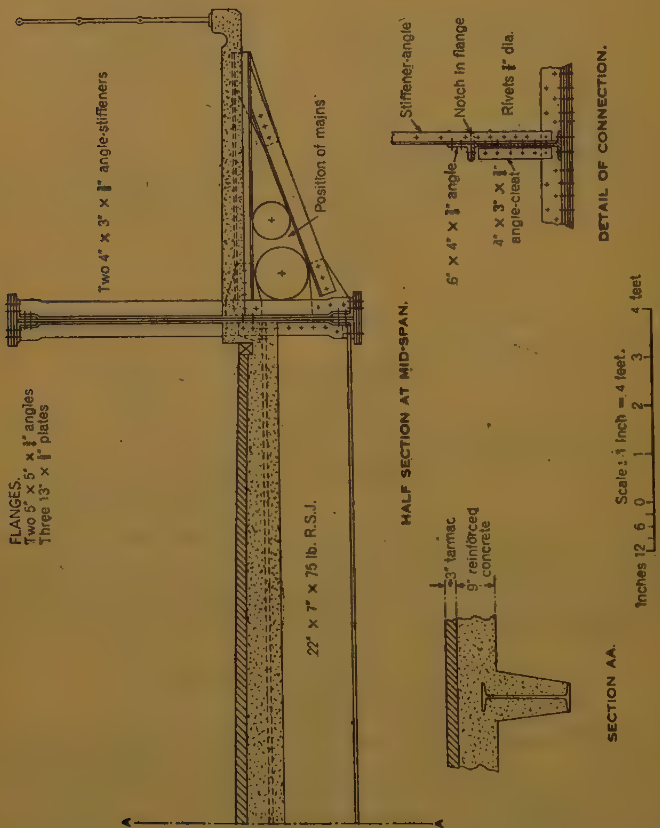
Hence, main tensile stress

$$= \frac{2{,}250 \times 12}{3{,}100} = 8{\cdot}7 \text{ tons per square inch,}$$

and main compressive stress

$$= \frac{2{,}250 \times 12}{3{,}650} = 7{\cdot}4 \text{ tons per square inch approximately.[1]}$$

Figs. 11.



HALF CROSS SECTION OF BRIDGE.

The flange-plates will be one $\frac{5}{8}$-inch plate 80 feet long, one $\frac{5}{8}$-inch plate 47 feet long (theoretical length), and one $\frac{5}{8}$-inch plate 33 feet 6 inches long.

[1] This method of determining the compressive stress is clearly only approximate, but owing to the uncertainty as to the exact effect of rivet-holes in the tension flange, it is on the safe side to assume that the position of the neutral axis remains unchanged.

The moment of inertia of the flange about the vertical axis will be 417 inch^4 units, so that, using formula (5), $L_w = 385$ inches; this is just less than the shortest plate, so that the effective moment of inertia will be 417 inch^4 units as above, and the loading coefficient will be 1·09 (see Table II). The critical stress f_w (formula (6)) will be 19·0 tons per square inch.

Allowing 25 per cent. extra stiffness to the cross girders for the concrete haunching, the secondary stress f_{b_1}, from formula (7), will be 0·34 tons per square inch, and the wind-stress from formula (8), taking an intensity of wind-pressure of 30 pounds per square foot, will be 0·13 tons per square inch.

The total combined stress will therefore be $7{\cdot}4 + 0{\cdot}34 + 0{\cdot}13 = 7{\cdot}87$ tons per square inch. Ignoring the yield-stress, the factor of safety on the buckling stress will be 2·4.

A cross section of half the bridge is shown in *Figs. 11*, together with details of the connections of the cross girders. In order to avoid secondary stress due to the dead-load deflection of the cross girders, it is recommended that the connections should be riveted up when most of the deck-concrete has been placed. The connection provided has a moment of resistance of about 18 tons-feet, which is about five times the moment of resistance of a pair of stiffeners.

The Council invite written communications on the foregoing Paper, which should be submitted not later than three months after the date of publication. Provided that there is a satisfactory response to this invitation it is proposed, in due course, to consider the question of publishing such communications.

Paper No. 5025.

"The Strength of Braced Cylinders."

By Thomas McElderry Megaw, M.Sc., Assoc. M. Inst. C.E.

(*Ordered by the Council to be published in abstract form only.*)

The resistance to instability failure of thin cylinders subject to uniform external pressure appears to have been first investigated by Fairbairn,[1] who, in 1858, published the results of a number of experiments on butt-riveted wrought-iron tubes, and deduced an empirical formula showing the relation of collapsing pressure to thickness, length, and diameter. His experimental results were the basis of many suggested empirical formulas for nearly 50 years. The first satisfactory theoretical formula, for a cylinder as distinct from a mere circular ring, was due to G. H. Bryan,[2] who in 1888, obtained for the collapsing pressure of an infinitely long cylinder the formula

$$p = \frac{1}{4} \cdot \frac{E}{1 - \sigma^2} \cdot \frac{t^3}{a^3}$$

where p denotes the collapsing pressure
- E „ Young's modulus
- σ „ Poisson's the ratio
- t „ the thickness of the cylindrical shell
- a „ the mean radius of the shell.

The results of further experimental work by R. T. Stewart, and by A. P. Carman and M. L. Carr were published [3] in 1905–06. They

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[1] W. Fairbairn, "Resistance of Tubes to Collapse," Phil. Trans., 1858, p. 389, and Brit. Assocn. Report, 1857, p. 215.

[2] G. H. Bryan, "On Stability of Elastic Systems," Proc. Cambridge Phil. Soc., vol. 6, p. 199, and "Application of Energy Test to a Long Thin Pipe," *op. cit.*, vol. 6, p. 287.

[3] A. P. Carman, "Resistance of Tubes to Collapse," Physical Review, vol. 21, p. 381, and Science Abstracts, No. 239 (1906).

A. P. Carman and M. L. Carr, "Experiments on Lap-Welded Steel, Seamless-Steel, and Brass Tubes," Univ. of Illinois Bulletin, vol. 3, No. 17, and Science Abstracts, No. 1986 (1906).

R. T. Stewart, "Collapsing Pressures of Bessemer Lap-Welded Steel Tubes, 3 to 10 ins. Diameter," Trans. Amer. Soc. Mech. Engineers, vol. 27, p. 730, and "Collapsing Pressure of Lap-Welded Steel Tubes," Trans. Amer. Soc. Mech. Engineers, vol. 29, p. 123.

used small seamless, and lap-welded, steel and brass tubes, and from their experiments they proposed empirical formulas. They suggested the existence of a "critical length" above which the collapsing pressure remained practically constant, and for the tubes used they found this length to be about 6 diameters.

The general theory of elastic stability was discussed by Professor R. V. Southwell in 1910 and subsequently.[1] He showed the results of "thin shell" theory to be a first and adequate approximation, and obtained for a thin cylinder of any length the formula

$$p = E\frac{t}{a}\left\{\frac{C}{n^4(n^2-1)}\cdot\frac{a^4}{L^4} + \frac{1}{12}\frac{(n^2-1)}{(1-\sigma^2)}\frac{t^2}{a^2}\right\}$$

where p, E, σ, t, a have the same meanings as above, and where

L denotes the length of the cylinder

n ,, the number of "lobes" in the form of collapse,

while C is a constant determined by the end conditions, and takes the value π^4 for the somewhat unpractical condition of ends restrained to a circular but not cylindrical form. For a long cylinder the first term becomes negligible and the formula reduces to that obtained by Bryan. The number of lobes, n, will be such as to make p a minimum. For long cylinders, n is 2, but for short cylinders it is a greater integer. This phenomenon had been observed by Fairbairn, but it remained unexplained until the appearance of Southwell's formula. It is further possible to show from that formula that the expression determining the critical length should be of the form $k\sqrt{a^3/t}$, and if k be suitably chosen a hyperbolic relation between p and L may be used for tubes shorter than the critical length. A suggested value for k is 3·12. Then for a "short" cylinder, p_∞ may be calculated from Bryan's formula, the critical length calculated as above, and the collapsing pressure found by increasing p_∞ in the ratio (critical length) : (actual length). Further work based on Southwell's formula has been done, largely by Professor G. Cook,[2] and tends to substantiate it.

Instability-Failure.

The application of Southwell's formula to the case of a cylinder stiffened at regular axial intervals by bracings is discussed in this

[1] Professor R. V. Southwell, "On the General Theory of Elastic Instability," Phil. Trans., Series A, vol. 213, p. 187, and "On the Collapse of Tubes by External Pressure," Phil. Mag., May, 1913, p. 687; September, 1913, p. 502; January, 1915, p. 67.

[2] G. Cook, "The Resistance of Tubes to Collapse," Report to British Assocn., 1913, p. 213, and "Collapse of Short Thin Tubes by External Pressure," Phil. Mag., October, 1925, p. 844.

Paper. The most general structure considered consists of a thin cylindrical shell with stiffening rings braced by a polygonal arrangement of struts. Two types of instability failure must be considered, to both of which Southwell's formula is applicable :—

(1) Failure as a long cylinder, the number of lobes in the distorted form being equal to the number of sides in the bracing polygon. The combined moment of inertia of skin-plate and stiffening-ring must be considered, so that the formula becomes :—

$$p = E\frac{n^2 - 1}{1 - \sigma^2} \cdot \frac{I_2 + t^3 L}{a^3 L}$$

where I_2 denotes the moment of inertia of the stiffening-ring,
and L „ the axial interval between the bracing-planes.

(2) Failure as a short cylinder, the length being that between the bracing planes. It is probably sufficiently accurate to calculate p_∞ for the skin-plate alone and to increase this in the ratio L_c/L, as suggested above.

Stress-Analysis.

The stresses in this structure are analysed by two methods. In the first it is treated as two-dimensional only, so that the combination of skin-plate and stiffening-ring is dealt with as a "thin rod"; the resulting formulas do not show how the stresses in the skin-plate are distributed longitudinally. The second method is three-dimensional, and makes use of the condition that the strain-energy is a minimum for an equilibrium position in order to determine the stresses, the type of deformation being assumed. It is difficult to express accurately the strain-energy per unit area of a curved plate, but a sufficiently accurate approximation may be used. The type of deformation is then assumed, and is chosen to conform with the "boundary conditions." The "amplitudes" of its various components are left as arbitrary constants to be determined later. For the braced cylinder it is assumed that any longitudinal section takes a form analogous to that of a continuous multi-span beam, while any circular cross section takes the most general form for a circular ring subject to symmetrical radial loading. With the boundary conditions, these assumptions enable the radial, tangential, and longitudinal displacements of any point to be expressed as linear functions of six arbitrary constants. From the assumed displacements the strains and changes in curvature are derived, and used in the strain-energy integral, which now becomes a second-

degree function of the arbitrary constants. The strain-energy, V, may be written as

$$V = V_1 + V_2 + V_3 - W$$

where V_1, V_2, V_3 denote respectively the energy in the shell plate, in the stiffening rings, and in the struts, and W denotes the work done by the external forces. From the condition that, for equilibrium, V must be a minimum, it follows that its partial differential with respect to each of the arbitrary constants may be equated to zero, so that the six simultaneous equations necessary may be obtained and solved. The values so obtained are then used in the expressions for the strains and curvatures, from which the stresses follow. This analysis is applied to the two-dimensional structure treated by the first method, and the results are compared.

The formulas for instability-failure and for stress are then illustrated by applying them to a particular cylinder and evaluating them, the dimensions used being those of a cylindrical cofferdam which actually collapsed while stiffened by circular angle rings, but not braced by struts.

The derivation of approximate stress-formulas for practical use is next dealt with, and the results given by them are compared with the more exact figures.

The conclusions drawn are embodied in the following suggested rules for design :—

(1) The possible types of instability-failure are of primary importance and govern the principal dimensions. The stresses are of secondary importance so long as the number of sides in the bracing polygon is not great, and can be checked once stability has been ensured. Stiffening-rings and hexagonal strutting should therefore be used.

(2) Provided that the corners of the hexagon can be made rigid, the section and spacing of the stiffening-rings should be chosen to comply with the following formula :—

$$\frac{I_2}{L} = \frac{(1-\sigma^2)}{(n^2-1)} \cdot \frac{pa^3}{E}$$

where p denotes the design pressure, incorporating a factor of safety of, for example, 2. For a hexagon, n has the value of 6.

(3) The thickness of the skin-plate should be determined to give the requisite strength for a "short" cylinder of length L, using the approximate formula

$$t^5 = p^2a^3L^2/E^2$$

(4) For the sake of economy of material, the stiffening-rings

should be "deep" radially, and they should be spaced at close intervals horizontally.

(5) The maximum stress in the skin-plate should be checked by the approximate formula

$$f = \frac{pa}{t}\left\{1 + \frac{5}{16}\,\frac{1 + \frac{18}{25}\cdot\frac{A_1}{A_2}\cdot\frac{t}{a}n^2}{1 + \frac{3}{10}\cdot\frac{A_1}{A_2}}\right\}$$

where $A_1 = tL$ denotes the sectional area of the skin-plate, and A_2 denotes the sectional area of the stiffening-ring.

(6) The maximum stress in the stiffening-ring should be checked by the approximate formula

$$f = \frac{pa}{t}\left\{\frac{1 + \frac{3}{2}\frac{y_1}{a}n^2}{1 + \frac{3}{10}\frac{A_1}{A_2}}\right\}$$

where y_1 denotes the distance from the neutral axis of the inside "fibre" of the ring.

(7) The section of the struts is not important, provided that they are reasonably rigid.

NOTE.

ENGINEERING RESEARCH.

In the November Journal a short account was given of The Institution Research Committee and of the five Sub-Committees which had been formed, namely, the Sub-Committees on Wave-Pressures, Vibrated Concrete, The Effect of Soils containing Sulphate Salts on Concrete and Metal Pipes, Reinforced-Concrete Structures for the Storage of Liquids, and Breathing Apparatus for Use in Sewers, etc. This was followed in the February Journal by notes on two additional Sub-Committees formed to carry on research on Special Cements and on Pile-Driving, whilst in this number appears a report of the formation of a Sub-Committee on Earth-Pressures. A résumé of a report on solubility by the Joint Sub-Committee on Special Cements is also included.

In the December Journal appeared the first of a series of notes and data relating to the work of certain research organizations under the control of the Department of Scientific and Industrial Research, where work of engineering interest is undertaken. These were followed by further notes in the January and February Journals, and continue in this number with a note on the work of the Fuel Research Station. Research of engineering interest is, however, carried out at Universities and elsewhere, and it is proposed to give from time to time accounts of such work. These will not be given in any special sequence. The first of such articles appears in this number and deals with the research work in engineering at Sheffield University.

A further innovation is the inclusion of notes on recent research publications of engineering interest throughout the world. They cannot claim to be comprehensive but an attempt is made to select those of greatest interest.

THE INSTITUTION RESEARCH COMMITTEE.

Sub-Committee on Earth-Pressures.

In 1925, the British Association, with their characteristic readiness to assist scientific research, appointed a Committee consisting of a number of engineers to investigate the subject of Earth-Pressures. With the approval of the Association, The Institution of Civil Engineers has now taken over the work and Committee *en bloc*, and it will continue to work as a Sub-Committee of the Research Committee of The Institution.

The work involves a number of difficult and elusive problems, but its importance is obvious. Although almost all engineering structures are built on earth and many are subject to lateral pressure

of earth, there is no material whose behaviour is so obscure and uncertain. The work with which the Committee have hitherto been associated has been largely an investigation into the mechanics of granular material carried out by Professor C. F. Jenkin, C.B.E., LL.D., F.R.S., mostly at the Building Research Station at Garston. The results of this work have been published by him in various forms—notably in Papers read before the Royal Society in 1931 and before The Institution of Civil Engineers in 1932. Unfortunately, owing to ill health, Professor Jenkin had to give up the work in August, 1933.

In July, 1934, the Committee (then under the British Association) considered two reports issued from the Building Research Station, the first by Professor Jenkin on "The Mechanics of Granular Materials" and the second, which was in the nature of an Appendix to the first, on "The Experimental Investigations of the Mechanics of Clay," which described in detail the experimental methods developed by Professor Jenkin.

Professor Jenkin's earlier work was essentially a fundamental investigation into the mechanics of granular materials, and his later work was directed towards the investigation of the properties of kaolin. Although the aspect of the investigation has now been changed, advantage is being taken of the experimental methods and technique which he developed, and the valuable ideas which he formulated on the dilatancy and compactibility of clays are being kept in mind.

In the present programme of work, the method of approach to the problem is less of the nature of a fundamental investigation and is inclined more towards the practical application of the results of laboratory tests. In consequence, experiments are not confined to one material, and all types of soil as they occur in nature are being examined. The term "soil" covers a wide range of materials which exhibit large variations in their mechanical properties. Because of this fact, one of the first objects of the work is to develop a system of soil-classification by means of which soils can be divided into broad groups according to their mechanical characteristics. Broadly speaking, the mechanical properties of a soil depend upon the following factors :—

(*a*) The nature of the raw constituents of the soil.
(*b*) The "structure" of the soil, or the way in which the soil-particles are arranged in the soil-skeleton.
(*c*) The water-content.

As a means of preliminary soil-classification, a method of characterizing a soil by identifying its raw constituents has been followed. This method, which was developed by American workers,

is based essentially on physical tests of an empirical nature. Although it is both rapid and useful, it is by no means wholly acceptable as a final method of soil-classification. Work is now in progress with the object of developing a classification-system based upon the experimental measurement of mechanical properties. For this purpose, tests such as those developed by Professor Jenkin for the measurement of compressive strength, consolidation and shear-strength are being employed.

In parallel with this work, investigations are being made into the influence on the mechanical characteristics of the structure of the soil as it occurs in its natural condition. For this research an apparatus has been devised and developed by means of which it is possible to obtain undisturbed soil-cores of 4-inch diameter down to depths of approximately 12 feet.

The second important object of the investigation is to correlate the results obtained in the laboratory with observations of actual structures. With this object in view, observations are being taken of :—

(*a*) The settlement of a building both during and after construction.

(*b*) Seasonal fluctuations in the level of road-slabs.

(*c*) Examination of failures in building structures which have occurred as the result of settlements.

(*d*) Examination of a failure in a retaining wall due to an embankment-slide.

(*e*) Examination of embankment-failures.

Experiments are being carried out at the Building Research Station on samples of soil collected from these sites, and with the accumulation of data, it is hoped that correlation may be possible.

The Sub-Committee consists of the following :—

Mr. F. E. Wentworth-Sheilds (Chairman).

Professor G. Cook.
Dr. T. E. N. Fargher.
Professor A. R. Fulton.
Professor F. C. Lea.
Dr. J. S. Owens.
Professor R. V. Southwell.
Dr. R. E. Stradling.
Professor W. N. Thomas.
Mr. E. G. Walker.
Mr. J. S. Wilson.

Joint Sub-Committee on Special Cements.

Report on the Solubility of Cements.

An interim report of the work of the British Sub-Committee on Special Cements on the solubility of cements has been prepared for consideration by the International Sub-Commission on Special Cements of the World Power Conference, and, by courtesy of the British Committee on Large Dams, an abstract of the report is given.

The solubility of cements is an important factor in the deterioration of concrete exposed to the action of pure and slightly-acid natural waters. Such solubility may be measured in various ways, and in their work the British Sub-Committee investigated the following methods :—

(1) An extraction method, evolved in Sweden, in which set neat cement after curing in water for the time desired, is crushed to a given fineness. The amount of lime dissolved by water from the crushed cement is taken as the measure of the relative solubility.

(2) Rengade's method, in which mortar specimens are subjected to the action of a jet of water impinging on their surface. The extent of wear or erosion is used as a measure of the relative solubility of the cement.

(3) A percolation-method, in which the lime-content of water which has percolated through the test specimen is taken as a measure of the solubility of the cement.

The extraction methods have the advantage of simplicity in operation and consistent results can be obtained. They are, however, open to the objection that on account of the partial destruction of the structure of the set material, the results may not give a fair index of the resistance of the cement. The Rengade method is qualitative rather than quantitative and takes a long time; and sufficient tests have not yet been made to show whether this method gives consistent results. Percolation-tests would at first sight appear to be the most valuable in that the conditions are more closely analogous to those obtaining in actual structures. Such tests are sometimes made in conjunction with permeability-tests on normal concrete using high water-pressures, but to obviate the use of high pressures and in the hope of obtaining more consistent results, these tests were conducted on lean mortars. Even so, the reproducibility of results is unsatisfactory.

As a result of the various tests it would seem, therefore, that the Swedish extraction method offers many advantages, but it is still uncertain whether it differentiates correctly in all cases between different cements. Further work requires to be done, however, before reaching any definite conclusions.

Tests have been carried out on normal Portland cements of varying composition, Portland blast-furnace cements and an experimental pozzuolanic cement. Of the various cements, all methods agree in showing that the experimental pozzuolanic cement has the greatest resistance to attack. According to the extraction method, one of the Portland blast-furnace cements ranks second, but this is not found to be so under the other methods of test.

THE WORK OF THE FUEL RESEARCH STATION AND COAL SURVEY LABORATORIES.

Introduction.

The problems connected with fuel which arose during the War led to the appointment, in 1917, by the Committee of the Privy Council for Scientific and Industrial Research, of the Fuel Research Board, " To investigate the nature, preparation, and utilization of fuel of all kinds, both in the laboratory and when necessary on an industrial scale," and the late Sir George Beilby was appointed Director of Fuel Research and Chairman of the Board.

Two facts were at once realized, (1) that investigations on the utilization of coal could not be carried to a successful issue on the scale usual in a laboratory, and (2) that a far more detailed knowledge than was available of the properties and characteristics of our various coal-seams was essential if the national coal-resources were to be used to the best advantage. The former led to the establishment of the Fuel Research Station at East Greenwich on a site leased at a peppercorn rent from the South Metropolitan Gas Company. This station includes not only the necessary laboratories, workshops, and offices, but a works where experiments on coal-carbonization, coal-cleaning, and so on, can be carried out on a scale comparable with industrial practice, so that the results can be applied with but little commercial development. The latter has led to the establishment in the principal coal fields of nine survey laboratories staffed by the Department and working in conjunction with the coal-owners on a systematic examination of the coal-seams.

The Physical and Chemical Survey of the National Coal-Resources.

The coal-survey has as its object the examination of the coal in this country as it exists underground and as it is, or might be, marketed. Coals differ more widely than is generally realized. They differ in coking properties, in the amount of gas and tar that they produce when heated, in the amount and nature of the ash they produce on combustion, in the amount of sulphur, chlorine, phosphorus, and other impurities they may contain, in inherent moisture, and in appearance and physical characteristics. Not only do the various seams differ, but the same seam may change from place to place, or may vary from floor to roof.

The first necessity in such a survey is to standardize analytical methods; those used in the past have differed appreciably in different laboratories, with the result that many of the published

results are not comparable with each other. The methods used in the coal survey have been standardized, and many of them have been adopted as British Standard methods.

The method used in examining a seam is to take a section, about 18 inches square, from the coal-face extending from floor to roof. This is transported to the laboratory where it is examined in detail. All bands having special characteristics are examined separately and an average sample of the seam " as mined " is also analysed. Such an examination shows whether it is desirable to divide the seam before marketing, as is frequently the case, or which bands may with advantage be rejected, either below ground or during subsequent grading on the surface.

An important part of the work is the correlation of the coal-seams. The same seam is frequently worked under different names in different parts of the coalfield, or the same name may be applied to different seams. Correct identification may be difficult, but is frequently of great practical importance, particularly when working through faulted areas.

The suitability of seams for carbonization, hydrogenation, boiler firing, etc., and their amenability to cleaning are also studied. For these investigations large consignments of the coals may be sent to the Fuel Research Station for examination on a scale comparable with industrial practice. In some cases samples have been taken of commercial grades of coal, and the results of analyses published. Investigations are also being carried out on the deliberate breakage of large coal to form graded sizes, and on the breakage that occurs during the cleaning, grading, and transport of coal. It is now possible, from the records of the Survey, to state where coal can be obtained of almost any desired properties, and the large-scale work is making it easier to predict with accuracy from laboratory tests the results that will be obtained in practice.

Coal Cleaning, etc.

The equipment available at the Fuel Research Station consists of a British Baum washer, an H.H. concentrator table, a Birtley pneumatic table, an Elmore vacuum floatation-unit, a pneumatic-jig cleaner developed by the Fuel Research organization, and a Dorr classifier and thickener for slurry-treatment. The machines are designed for a throughput of 2 tons of coal an hour, with the exception of the concentrator table, which has a higher capacity. Ancillary apparatus consists of elevating and conveying gear, power screens, and a swinging-hammer-type crusher. A laboratory for analysis and research is attached, as well as a room fitted with apparatus necessary for the preparation of samples for analysis.

Apart from the investigations arising from the work of the Coal Survey mentioned above, four main lines of research are being followed, (*a*) the development of a pneumatic-jig cleaner which has reached the stage of 2 tons of coal an hour, (*b*) a study of the moisture-holding properties of coal in connection with dry cleaning and screening (the Survey co-operating), (*c*) a study of the conditions necessary for the cleaning of the various types of fine coal by froth-floatation, and (*d*) an investigation of the use of flocculating agents for the clarification of washery water. From time to time, quantities of coal are specially cleaned or graded for various research programmes at the Station such as hydrogenation and pulverized fuel.

Carbonization.

The experimental carbonizing plant comprises full-size settings of horizontal gasworks retorts, intermittent chamber ovens and continuous vertical retorts; each setting capable of dealing with 10 to 20 tons of coal a day and fitted so that accurate scientific data can be obtained. Other smaller settings are also installed to deal with charges of 1 or 2 cwt. The capacity of the plant for gas-production is thus equal to that of a gasworks supplying a small town of about 16,000 inhabitants. The gas and tar produced, which is surplus to requirements, is bought by the South Metropolitan Gas Co., and coke is disposed of by sale to the public or to H.M. Office of Works.

Research on carbonization processes is directed towards improving the yields of gas and saleable coke and to the production of cokes and tars suitable for various purposes. Substantial increases in the thermal yield of horizontal retorts have been obtained by recirculating flue gases and also by steaming the charges during the later part of the carbonizing period. By varying the carbonizing conditions and blending of coals, cokes are obtained ranging from hard metallurgical coke to solid smokeless fuel suitable for open domestic fires, and the range of coals available for these purposes has thereby been widened. The effect of the variations on the tar produced is also observed so that it is possible, for example, to produce at will tars eminently suitable for conversion to motor spirit by hydrogenation.

A special study has been made of the effect of lowering the temperature of carbonization so as to produce a free-burning smokeless domestic fuel, and a high yield of tar, from which petrol and oils can be obtained. This has the double object of reducing atmospheric pollution due to smoke, and of increasing the supply of oil fuels from home sources.

Samples from seams sent in by the several Survey Stations are also tested as regards the suitability of the coals for different

carbonizing treatments; the samples may range in size from a few pounds to several hundred tons.

From time to time inquiries are dealt with from other parts of the Empire regarding the treatment of native deposits of brown coal, lignite, peat, etc., as well as various vegetable products, with a view to the production from these local resources of solid and liquid fuels suitable for railway and road-transport services.

Hydrogenation.

By treating coal with hydrogen at pressures of 200–400 atmospheres and temperatures of 450–500° C. in the presence of catalysts the bulk of the coal substance can be converted into oil. The mechanism of this process is being studied together with the nature of the products obtained. The equipment available includes a small continuously-working plant capable of treating about ¼ cwt. of coal a day, which is used for testing coals in connection with the Survey, as well as for experiments on the process itself.

A similar treatment can be used to convert tars or heavy oils to light oils and motor spirit, and a plant with a throughput of about 300 gallons of material a day has been developed and erected. Tars produced at "low" temperatures are readily amenable to treatment, as are the "creosote" fractions of ordinary gasworks-tars. The latter tars are more difficult to treat as a whole, and the problem is being further studied.

Apart from the plant mentioned above the equipment includes a number of smaller converters both for dealing with static charges, and for continuous operation.

Pulverized Fuel.

The equipment available for experiments on steam-raising consists of a small Babcock & Wilcox water-tube boiler, and a Lancashire boiler, both having a rated load of 5,000 lb. of steam per hour. Both are arranged for operation on powdered fuel, and are supplied from a bin and feeder system fitted with a coal-dryer, tube-mill, and Fuller Kenyon pump. A Scotch boiler with a rated load of 8,000 lb. of steam per hour is being installed. Arrangements are being made for this to be hand-fired, or to use liquid or pulverized fuel. The experiments have been directed to increasing the flexibility of pulverized-fuel burners for use with Lancashire and other boilers having a small water-cooled combustion-space, both as regards the nature of the coal and the load.

Two new simple types of pulverized-fuel burners have been

developed at the Station, together with a method of ensuring equal supplies of fuel and air to two or more burners fed from the same source. These are now in commercial use. It has been found possible, by using these appliances, to obtain over long periods double the rated load from Lancashire boilers.

General.

The laboratories at the Fuel Research Station not only carry out the analytical and other control work in connection with the large-scale experiments but are engaged on a number of problems such as the constitution of coal, the synthesis of liquid fuels, lubricating oils and suspensions of coal in oil. Methods of analysis are continually under review in conjunction with the Survey laboratories, and samples are distributed at intervals as a check on the technique adopted and to obtain a measure of the accuracy obtained. Private laboratories can participate in this scheme for "check samples," and a number have done so.

The intelligence section abstracts all relevant literature dealing with fuel, and weekly summaries are distributed to the staff. Every endeavour is made to supply references to inquirers. The results of the investigations are published in the Annual Report of the Fuel Research Board, in Technical Papers and Survey Papers issued by H.M. Stationery Office, and in numerous papers read before scientific and technical societies.

RESEARCH WORK IN ENGINEERING AT SHEFFIELD UNIVERSITY, JANUARY, 1936.

Several researches of a fundamental nature of interest to engineers of all branches of the profession are being carried out here and, as befits the centre of the steel industry, the major part of the research concerns ferrous metals. The work may be divided into :—

(1) Structural Research.
(2) Research on Ferrous Metals.
(3) Research on Reinforced Concrete.
(4) Hydraulic Research.

(1) *Structural Research.*

Attention has been directed to the effect of repeated stresses on structural elements, with particular reference to discontinuities in form such as occur in welded, riveted, and bolted elements. A machine has been constructed in which beams up to 8 feet long

by 5 inches deep by 3 inches wide can be repeatedly subjected, over a length of 12 inches, to a uniform bending-moment, thus eliminating complication due to shear-stresses, at a frequency of about three hundred vibrations a minute. The stress-cycle can be varied at will between zero and a maximum stress or between different stresses of the same sign, the limits being determined by the positive vibration of the beam between definite deflections.

Tests have been carried out on both mild-steel and "Chromador"-steel plain joists, plain joists with a welded butt-joint and joists with holes in the flanges. Further tests are intended on thick welded plates and on beams joined by cover-plates with the alternatives of riveted, bolted, and welded connections. The results of such tests are compared with tests on simple-riveted, bolted, and welded joints in a flat bar, carried out on a Haigh repetition-stress machine. Results of considerable importance are being obtained, which may lead to a revision of permissible stresses in structures subject to vibration. It is proposed to extend this research to reinforced-concrete beams, and a larger machine capable of taking beams up to 10 feet long by 12 inches deep by 6 inches wide is being constructed.

(2) *Research on Ferrous Metals.*

A large amount of research has been and is still being carried out on the behaviour of steels under repeated stresses. These include experiments on thin plates under repetition-stresses, in which the behaviour under repetition-stresses of cold-rolled strips of mild steel and alloy-steels and the effect of holes of various sizes, riveted joints, etc., have been studied in a Haigh repetition-stress machine.

The effect of surface-discontinuities and corrosion-conditions upon the behaviour of materials under repeated stresses has also been studied. Discontinuities of form such as are produced by keyways, holes, etc., and the condition of the surface such as black or bright, in the dry or exposed to corroding influences, are found to influence considerably the fatigue-range. The effect of corrosion is particularly striking and it is found, for example, that high-tensile steel in a corrosive medium has, for a specified number of repetitions, about the same fatigue-range as a low-tensile steel. These repetition tests have been carried out in various ways in Haigh, Wöhler, constant bending-moment, impact, etc., machines.

In order to study the subject of welding as applied to boiler-plates, tests on welds under repeated stresses at normal and elevated temperatures have been carried out. A special machine has been devised in which the weld is at the centre of a test-piece in the form of a beam, maintained at a known temperature and subject to

repetitions of constant bending-moment along its length. The range of stress is fixed by the amplitude of oscillation and can be accurately determined by optical deflectometers. It can be varied between positive and negative values as desired, and the frequency can be varied between five hundred and one thousand vibrations a minute.

Since in high-frequency repetition-stress machines there is not time between reversals of stress for creep of the metal to take place, low-frequency fatigue-tests at elevated temperatures are being carried out. A machine has been constructed in which a tensile-test specimen is subject to a harmonic cycle of strain which can be adjusted to give any range of tensile stress at a frequency between two and five cycles a minute.

Fatigue-tests on springs at normal and elevated temperatures have brought out the fact that the surface of springs should be smooth and polished. These tests were carried out in special spring-fatigue-testing panels, where the spring is vibrated at its natural periodicity through a definite amplitude at ordinary or elevated temperatures, and also in other special machines designed for testing wires under repeated stresses.

Other research work on metals includes an extensive study of creep and age-embrittlement under static loading at high and at normal temperatures of low-carbon and alloy-steels. A battery of about a dozen machines is in simultaneous use for this research.

The effect of cold work upon the properties of metals is also studied. For this the University is well equipped with its own cold-rolling plant and wire-drawing mill, and an extensive research on cold-working of metals is being carried out in co-operation with the Metallurgical Department for the Worshipful Company of Ironmongers.

The testing equipment available includes in addition to the machines designed for special tests the following machines :—

Repetition-stress.

- Haigh.
- Wöhler.
- Rotation under constant bending-moment with or without torque, three machines.
- Haigh-Robertson Euler-column fatigue-testing machine.
- Torsional fatigue-testing machine with or without added tension.

Static-testing.

210 ton concrete-testing machine.
80 ,, Armstrong ,, ,,
50 ,, Buckton ,, ,,

100,000 lb. Riéhlé testing machine.
10 ton Buckton " "
10,000 lb. Olsen " "
10,000 lb. Dennison " "
Armstrong bend-testing machine.

Sankey repeated-bending machine.
Stanton impact-testing machine.
Hardness-testing machines of many types, etc.

(3) *Research on Reinforced Concrete.*

This includes research on strain-distribution in reinforced-concrete beams. The original object of this research was to investigate the validity of the fundamental assumptions in reinforced-concrete design.[1] The work is being developed to include various forms of reinforcement and in relationship to other tests.

Research on the corrosion of reinforcement is also in hand. Reinforced-concrete specimens in which the bond of the reinforcement was destroyed by slight drawing-out of the reinforcement, made 22 years ago, are broken from time to time to detect evidence of corrosion.

Research has also been carried out on the grading of aggregate, slump tests, water-cement ratio, etc., and tests are being made on cement mortars to determine the influence of size and form of test specimens.

(4) *Hydraulic Research.*

In order to determine the loss of head in pipes of various sizes with constant roughness-ratio, flat sheets of metal in which fine grooves have been machined are formed into pipes. Various sizes are being constructed, but the ratio of depth of groove to diameter of pipe is kept constant. The investigation aims at determining the effect of the scale and the roughness-factor upon frictional losses.

The flow through small orifices of oils of known viscosities under high pressures, such as occur in compression-ignition oil engines, is under investigation. The flow under very high pressure-gradients of viscous fluids through fine tubes is so much outside the normal range of hydraulic experience that there is no justification for assuming, without experimental evidence, that equations of flow devised for normal conditions apply. Apparatus has been made from which the flow under high pressures through small orifices having various ratios of length to diameter is being determined.

[1] Prof. F. C. Lea, "Fundamental Assumptions in Reinforced-Concrete Design." Inst. C.E. Selected Engineering Paper, No. 164, 1934.

The above researches are being carried out under the direction of Professor F. C. Lea, O.B.E., D.Sc., M. Inst. C.E., Dean of the Faculty of Applied Science of Sheffield University.

NOTES ON RESEARCH PUBLICATIONS.

In connection with research on the properties of engineering materials the following papers have been published from the National Physical Laboratory: An investigation of the nature of creep under stresses produced by pure flexure (*Inst. Metals Jnl.*, **57**, *121*).[1] Alloys of magnesium—Part III; constitution of the magnesium-rich alloys containing aluminium and cadmium (*Inst. Metals Jnl.*, **57**, *287*). The behaviour of mild steel under prolonged stress at 300° C.—Part II; experiments on concentrated stress in notched and drilled specimens (*Iron & Steel Inst. Jnl.*, **132**, *281*). Investigation of the behaviour of metals under deformation at high temperatures—Part I; structural changes in mild steel and commercial irons during creep (*Iron & Steel Inst. Jnl.*, **132**, *179*). The inter-relation of age-hardening and creep performance—Part I; age-hardening of nickel-silicon-copper alloys (*Inst. Metals Jnl.*, **57**, *141*). Research on the plastic flow of concrete is described in *Ohio State University Studies Bulletin No. 91* and a survey of previous work on the subject is included. Alternating tension and compression and tension fatigue-tests on large welded joints under repeated loadings are dealt with in *Stahlbau, 1935*, **8**, *164–5*, and in a book: "Fatigue tests on welded joints" by Adrian, Memmler, Bierett, Gehler and Graf (*V.D.I. Verlag, Berlin, 1935*). The behaviour of fillet welds when subjected to bending stresses is the subject of an article in *Am. Weld. Soc. Jnl., 1935*, **14** (9) *Supp., 1–16*. The present state of the investigations of the Wire-Ropes Research Committee into the deterioration of colliery winding-ropes in service is given in *Safety in Mines Research Board Paper No. 94*; the chief cause of deterioration is shown to be corrosion-fatigue. Research on the resistance of nitrided austenitic manganese-steel to sea-water corrosion (*Inst. Phys. & Chem. Research* (*Tokyo*), *Scientific Paper, No. 615, 221*), shows it to be stainless under these conditions.

Research on the production and preservation of materials includes the following:—The warming of concrete during frosty weather by the passage through it of electric currents is described and quantitative results are given in *Schweizerische Bauzeitung*, **107**, *55*. The technique of pumping concrete and the desirability of the use of

[1] The figure in heavy type is the number of the Volume; the figure in brackets the number of the Part; and that in italic type the number of the Page.

continuous concrete-mixers are discussed in a paper entitled "Betonnières Automatiques" (*Compte Rendu des Travaux de la Société des Ingenieurs Civils de France, July–Aug., 1935*). The mechanism of corrosion of tinplate is the subject of *Technical Publication Series A No. 30* of the International Tin Research and Development Council.

Dealing with mass structures: in an article on the distribution of earth pressure under a uniform surcharge according to Coulomb's theory (*Bautechnik, 1935,* **13** (*20*), *253–5*), a criticism of Culmann's method is given. The bearing capacity of the soil and its resistance to deformation is investigated according to Schultz's formulas in *Bautechnik 1935,* **13** (*17*), *219–20.* A mathematical analysis according to Weber's theory of the stress under foundations is given in *Proc. Royal Swedish Inst. for Engineering Research, Vol. 137.* Seepage under dams and uplift pressures are dealt with in papers on the design of weirs on sand-foundations and on pressures under a model of Panjinad Weir and under the prototype (*Proc. Punjab Engg. Congress,* **23,** *67 and 129*). In the report of the Punjab Irrigation Research Institute for the year ending April, 1935, electrical and physical methods of studying seepage-flow in models are discussed. Curves showing the variation of temperature at various places in the interior of the Requejada Dam are given in *Revista de Obras Publicas, 1 Feb. 1936,* **57.** The deformation of slabs is dealt with in a mathematical investigation of pressure-distribution through an elastic stratum (*Akademie der Wissenschaften in Wien, Mathematisch-naturwissenschaftliche Klasse,* **144** (*5/6*), *267–75*).

Framed structures are the subject of the following investigations. Bending stresses in welded connections for transverse girders in railway bridges are considered in *Bauingenieur, 1935,* **16** (*41/42*), *435–8,* fatigue of the weld being taken into account. The calculation of the horizontal vibration of framed buildings by the energy method is given in *Bauingenieur, 1935,* **16** (*47/48*), *485–9,* and (*49/50*), *496—500.* The study of the deformations and a computation of the stresses in tall building-frames by means of mechanical models (*Proc. Am. Soc. Civ. Eng.,* **62** (*1*)), is found to give reliable results. An analysis of the stresses in rectangular portals the legs of which are supported eccentrically is given in *La Technique des Travaux, Jan. 1936.* An experimental determination of impact-effects and tests on models for the calculation of stresses in frame-arch spans for railway loadings are described in *Indian Railway Board Technical Paper No. 294.* The distribution of wind-pressure on buildings as studied by means of model tests in an experimental wind-tunnel at the Institut Aerotechnique de Saint-Cyr is described in *Travaux, Jan. 1936.*

The construction and driving of screw-piles in reinforced concrete is described in *Génie Civil*, **108**, *135*: the screwing of the piles is facilitated by the provision of water-jets at the nose of the pile.

Research on heat engines includes an account of the difficulties experienced and overcome in the design and operation of a mercury boiler and turbine (*Journal of the Franklin Inst., Dec. 1935*). An experimental and mathematical study of the convection of hot air from bodies of various shapes is given in *Chaleur et Industrie, Jan. 1936*. A paper on flame gases in the light of recent research (*Proc. S. Wales Inst. Engrs.*, **51** (*6*)), indicates the presence of long-lived latent energy in the gases, which in one case amounted to as much as 29 per cent. of the heat of combustion. The calibration of small venturi meters suitable for metering lubricating oils where the effect of viscosity is not negligible is discussed in *Instruments, the Magazine of Measurement and Control, Jan. 1936*.

A wide range of electrical research is covered by the *15th Annual Report of the British Electrical and Allied Industries Research Association*. It includes fundamental and practical research on insulating materials and oils, a study of conductors, control apparatus, steam condensers, turbines and boilers. Interference with radio and telephone circuits has been investigated and work done on surge phenomena and other miscellaneous items. Equations for calculating three-phase symmetrical components are given in *University of Washington Engg. Experiment Station, Bulletin No. 84*.

The following researches on roads and railways have been noted. "Contribution to the knowledge of the physical nature of bituminous road materials: agglomerating power determinations," by E. Flister (*Alb. Sayffaerth G.m.b.H., Berlin, 1934*), gives methods of determining the binding power of various materials. A method of designing non-rigid highway surfaces is set out in *Univ. Washington Engg. Experiment Station Bulletin No. 83*; formulas are derived for the bearing power of gravel, crushed rock, bituminous macadam and similar materials. Research on the design of concrete road slabs based on experimental results is described in an article in *Public Roads* (issued by the U.S. Dept. of Agriculture), *Dec. 1935*. A determination of the air-resistance of various makes of motor vehicles by full-scale wind-tunnel tests and by coasting experiments is described in *Kansas State College Bulletin 20*. A mathematical analysis of the resistance of a four-wheeled railway truck is presented in *Glasers Annalen*, **118**, *25–30*.

In connection with water transport, harbours and rivers: the protection of ships' hulls against marine corrosion is dealt with in *Trans. N.E. Coast Inst. Engrs. & Shipbuilders, 1936*, **52**, *Part 4*; the conclusion is reached that the use of special steels is not

economical. A method of testing ship-models in open water, thus avoiding the use of a Froude tank, is described in *University of Washington Engg. Experiment Station, Bulletin No. 87, 1935.* A note on the calculation of wave-pressures against a vertical sea-wall with a horizontal foreshore is given in *Annales des Ponts et Chaussées, 1935* (*11*). This theory is shown to give good agreement with observed pressures, but does not deal with the case of a wave breaking against a sea wall where impact pressures result. The stability of regime of silt-carrying rivers as studied by model tests, and the effect of defining the channel by pitched banks, are described in *Bautechnik, 4 Feb., 1936.*

Research publications on the subject of air transport include the following *Aeronautical Research Committee Reports and Memoranda*:—No. 1636, Tests on aerofoil flaps in the compressed-air tunnel; No. 1665, Rolling and yawing moments on half wings with various modifications of wing tips; No. 1666, Full-scale tests on the longitudinal control of a low-wing monoplane, with special reference to wing wake; No. 1673, Wind-tunnel tests of high-pitch airscrews. Cooling problems with particular reference to the work of the 24 ft. R.A.E. tunnel are dealt with in *Journal Royal Aeronautical Soc.*, **40**, *102.*

Research on hydraulics includes: a study of water-hammer in pipes of varying cross section by a graphical method (*La Technique Moderne*, **28**, *75–80*); "Modern conceptions of the mechanics of fluid turbulence," a paper giving the latest developments in the theory of flow through pipes (*Proc. Amer. Soc. Civ. Engrs.*, **62**, (*1*)); in the same journal a comparison is made of sluice-gate discharge in a model and its prototype; the error of assuming as constant the coefficient in the formula for the discharge of a Cippoletti weir is given in *Univ. Washington, Engg. Experiment Station, Bulletin No. 85.*

The following miscellaneous researches are of interest to the engineer. A study of superconductivity in the light of accepted principles is given in *Trans. Royal Canadian Inst.*, **20**, *305–333.* Earthquake research is dealt with in the preliminary geological report on the Quetta earthquake (*Records of the Geological Survey of India*, **69** (*2*)); it is considered therein that buildings designed for an acceleration of 4·8 feet per second per second should have an ample margin of safety. The *Bulletin of the Earthquake Research Inst., Tokyo*, **13** (*4*), gives the results of mathematical investigations and model experiments on the transmission of elastic waves through the earth.